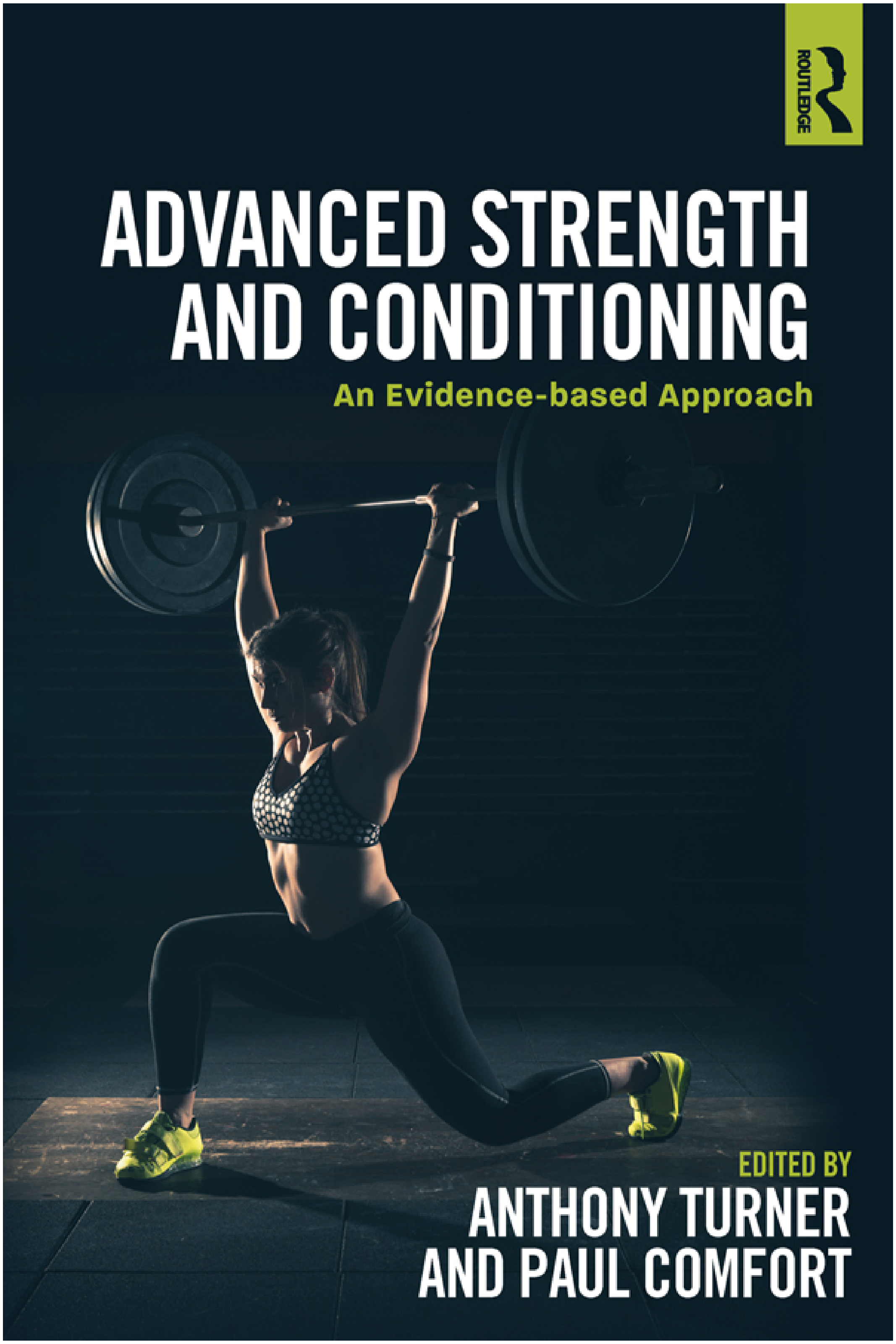
ADVANCED STRENGTH AND CONDITIONING

An Evidence-based Approach

EDITED BY
ANTHONY TURNER
AND PAUL COMFORT

ROUTLEDGE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Advanced Strength and Conditioning

Becoming an effective strength and conditioning practitioner requires the development of a professional skills set and a thorough understanding of the scientific basis of best practice. Aimed at advanced students and beginning practitioners, this book explores the latest scientific evidence and applies it to exercise selection and programming choices across the full range of functional areas in strength and conditioning, from strength and power to speed and agility.

With coverage of data analysis and performance feedback, both vital skills for the contemporary strength and conditioning coach, this concise but sophisticated textbook is the perfect bridge from introductory study to effective professional practice. Written by experts with experience in a wide variety of sports, its chapters are enhanced by extensive illustrations and address key topics such as:

- fitness testing and data analysis
- developing strength and power
- motor skill acquisition and development
- strategies for competition priming
- monitoring training load, fatigue and recovery.

Advanced Strength and Conditioning: An Evidence-based Approach is a valuable resource for all advanced students and practitioners of strength and conditioning and fitness training.

Anthony Turner is the Director of postgraduate programmes at the London Sport Institute, Middlesex University London, UK, where he is also the Programme Leader for the MSc in strength and conditioning. Anthony consults with the British Military, Queens Park Rangers Football Club, Saracens Rugby Club and various Olympic and Paralympic athletes. He was also the head of physical preparation for British Fencing between the London and Rio Olympics. Anthony is accredited (with distinction) with the National Strength and Conditioning Association and the UK Strength and Conditioning Association (UKSCA), and was awarded the 2015 UKSCA coach of the year for education and research. Anthony has published over 60 peer-reviewed journal articles, is an associate editor for the *Strength and Conditioning Journal*, and completed his PhD examining physical preparation in Olympic fencing.

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Advanced Strength and Conditioning

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Edited by Anthony Turner and Paul Comfort

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

First published 2018
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

and by Routledge
711 Third Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book has been requested

ISBN: 978-1-138-68735-6 (hbk)
ISBN: 978-1-138-68736-3 (pbk)
ISBN: 978-1-315-54234-8 (ebk)

Typeset in Berling and Futura
by Keystroke, Neville Lodge, Tettenhall, Wolverhampton

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Abbreviations

1RM	one repetition maximum
ADP	adenosine diphosphate
AMP	adenosine monophosphate
AO	antioxidant supplements
ATP	adensosine triphosphate
BASES	British Association of Sport and Exercise Sciences
C	cortisol
CC	contractile component
CHO	carbohydrate
CK	creatine kinase
CMJ	countermovement jump
CNe	critical non-essentials
COD	change of direction
CODS	change of direction speed
COM	centre of mass
COMP	competition
CSA	cross-sectional area
CT	complex training
CWI	cold water immersion
DJs	drop jumps
DLPFC	dorsolateral prefrontal cortex
dm	dry muscle
DRF	decrease in the ratio of force
EF	extrafusal fibers
EIMD	exercise-induced muscle damage
EMG	electromyography/electromyographic/electromyogram
EUR	eccentric utilization ratio
FI	fatigue index
FMS	Functional Movement Screen

FO	functional overreaching
FPPA	frontal plane projection angle
FTot	support phase
F-v	Force-velocity
GAS	general adaptation syndrome
GCT	ground contact time
GH	growth hormone
GPT	general physical training
GRF	ground reaction force
GSAC	gastrocnemius-soleus-achilles complex
H^+	hydrogen ion
HB	haemoglobin
HF	horizontal force
HIIT	high-intensity interval training
HR	heart rate
IPC	ischemic pre-conditioning
KP	knowledge of performance
KR	knowledge of results
LESS	Landing Error Scoring System
LG	lateral gastrocnemius
LLR	long-latency response
LSD	long slow distance running
LSI	Limb Symmetry Index
LT	lactate threshold
LTP	lactate turnpoint
M1	primary motor cortex
MAE	method of amplification of error
MAS	maximal aerobic speed
MCT	monocarboxylate transport proteins
MG	medial gastrocnemius
MLR	medium-latency response
MLSS	maximal lactate steady state
MS	muscle spindles
MSFT	Multi-Stage Fitness Test
mTOR	mammalian target of rapamycin
MTS	muscle-tendon stiffness
MTU	musculotendinous (muscle-tendon) unit

MVC	maximal voluntary contraction
MVIC	maximal voluntary isometric contraction
NFO	non-functional overreaching
OBLA	onset blood lactate accumulation
OT	overtraining
PAP	post-activation potentiation
PCr	phosphocreatine
PDH	pyruvate dehydrogenase
PEC	parallel elastic component
PFK	phosphofructokinase
PFPS	patella-femoral pain syndrome
PGC-1α	peroxisome proliferator-activated receptor gamma coactivator 1-alpha
P_i	inorganic phosphate
Pmax	maximum horizontal external power output
PMC	premotor cortex
PT	plyometric training
P-v	power-velocity
RE	running economy
RF	ratio of forces
RFD	rate of force development
RM	repetition maximum
ROM	range of motion
ROS	reactive oxygen species
RPE	rate of perceived exertion
RSA	repeated-sprint ability
S&C	strength and conditioning
SEC	series elastic component
SFRA	stimulus-fatigue-recovery-adaptation theory
SJ	squat jump
SLH	single leg hop
SLR	short-latency response
SLS	single leg squat
SM	self-motivate
SMA	supplementary motor area
SPPCs	strength-power potentiating complexes
SSC	stretch-shortening cycle

SSPT	sport-specific physical training
T	testosterone
TCA	tricarboxylic acid
TJA	tuck jump assessment
TL	training load
TWI	thermoneutral water immersion
v0	theoretical maximal force (F0) to the theoretical velocity
VCCF	cautionary coach feedback
VEGF	vascular endothelial growth factor
VF	vertical force
VHS	Very Heavy Sled
VL	vastus lateralis
$\dot{V}O_2$ max	maximal oxygen uptake
$\dot{V}O_2$ peak	peak oxygen uptake
vOBLA	velocity at the onset of blood lactate accumulation
VPCF	positive coach feedback
v$\dot{V}O_2$ max	velocity at $\dot{V}O_2$ max
WBC	whole body cryotherapy
YIRT	Yo-Yo Intermittent Recovery Test

CHAPTER 1

Strength and conditioning: Coach or scientist?

Perry Stewart, Paul Comfort and Anthony Turner

With the growth of professionalism and the significant financial incentives (television rights, sponsorships, wages, merchandise) associated with elite sport, it is unsurprising that the demand for scientific support services is on the increase in many sports. One of the disciplines that has experienced such growth and popularity is strength and conditioning (S&C). S&C coaches are employed through government-funded organizations (national institutes of sport), educational establishments (schools, colleges and universities), professional sport clubs, commercial performance facilities and by individual athletes (Dawson et al., 2013). Fundamentally, the role of an S&C coach is to enhance athleticism and decrease the risk of sports injuries through the testing, evaluation and prescription of appropriate exercises in close collaboration with sport coaches, physiotherapists and other relevant professionals. However, despite its growing acceptance within the interdisciplinary team, S&C coach responsibilities widely vary, which is poignantly highlighted in job specifications and further complicated by the different job titles advertised, which have recently included: S&C specialist, physical preparation coach, movement specialist and performance specialist to name a few. What is known however, is the role of an S&C coach is multifaceted and that sporting performance in the context of physical preparation is influenced by much more than simply what an athlete does in the weight room or on the track/field/court. The

roles and responsibilities of today's S&C coach extending far beyond that of designing and implementing training programmes.

It is pertinent for all current and aspiring S&C coaches to appreciate the breadth and depth of knowledge and skills required to effectively work in, and excel in, the discipline of S&C. Arguably the role now is a lot different to the one carried out as little as 10 years ago, and we must appreciate its evolution towards a practitioner who is just as much a scientist as a coach. Therefore, the aim of this introductory chapter is to review the necessary attributes required to be an effective practitioner within the S&C industry. This will be achieved by exploring and further exemplifying the facets of S&C coaching. It is the intention that this will in turn set the context and significance of each chapter that follows, where all these components are discussed in far greater detail.

THE COACH

It is prudent to start our review at the origin of the role, coaching. The role of a coach, regardless of type (technical, S&C etc.) or sport, is to improve athletes' physical, mental and emotional performance, in preparation for sporting competition (Dorgo, 2009). Previous conceptual models of coaching have emerged from different theoretical perspectives including leadership, expertise, coach-athlete relationships, motivation and education, highlighting the complexity of a coach's role – all of which are important. Côté and Gilbert (2009), define coaching effectiveness as:

> The consistent application of integrated professional, interpersonal and intra-personal knowledge to improve athletes' competence, confidence, connection, and character in specific coaching contexts.

This definition can be better understood when the three components of this model (knowledge, outcomes and contexts) are considered. The coach's skills, attitudes and behaviours – collectively referred to as 'knowledge' – are separated into three interrelated categories:

1) Professional knowledge: Expert knowledge of subject (and sport) specific theories. Within the realm of S&C this is likely to include:

understanding the demands of competition; how to plan and programme components such as strength, power, speed, and metabolic conditioning; application of macro, meso and micro-cycles; principles of dynamic correspondence; how to differentiate training for different populations; and pedagogical theories.

2) Interpersonal knowledge: To be successful, coaches have to interact effectively with their athletes, head and assistant coaches, as well as parents and other key stakeholders. This refers to the soft skills (sometimes referred to as emotional intelligence) required to identify, use, understand and manage interactions.
3) Intrapersonal knowledge: Described as self-awareness and introspection, the ability of a coach to critically reflect. Gilbert and Trudel’s (2002) research examined good coaches and how they translate experience into knowledge and skills through reflection. In summary, a coach’s ability to maximize athletes’ outcomes rests not only on extensive professional and interpersonal knowledge, but also on constant introspection, review and revision of one’s practice (Côté and Gilbert, 2009).

Traditionally, coaches focus the majority of attention towards developing professional knowledge. Although expert knowledge of the industry and the sport is essential, it is narrow-minded to assume this component alone will lead to being an effective coach and having a successful career. In fact, it is the integration of professional knowledge, how well a coach connects with others (interpersonal skills), and how open they are to continued learning and self reflection (intrapersonal skills) that will determine how effective and successful an S&C coach will be.

The second component of effective coaching focuses on ‘athlete outcomes’, which typically fall into performance gains (successful performances and player development) and positive psychological responses (high level of self esteem, intrinsic motivation, enjoyment and satisfaction). Côté and Gilbert (2009) identified four athlete outcomes, namely: competence, confidence, connection and character/caring. It is believed that the coach responsible for designing appropriate training conditions can enhance all of these. These are explained in relation to the S&C industry below:

- Competence: Enhanced physical capabilities. This may include improving an athlete's movement proficiency, strength, power, speed and endurance performance. Such qualities are commonly measured and assessed using field or laboratory based tests. However, a vital consideration for any S&C coach is whether enhanced athletic ability corresponds to improved sporting performance (which is harder to objectively measure in the majority of cases).
- Confidence: Improved sense of overall positive self-worth. A coach and athlete should agree on achievable objectives and the coach ought to design programmes that allow the athlete to succeed.
- Connection: Facilitating positive bonds and social relationships inside and outside of sport. A coach can encourage communication between athlete and staff, parents and non-sport peers.
- Character: Encouraging moral attributes such as respect, integrity, empathy and responsibility. Encourage athletes to take responsibility for their own environment, programming and personal standards.

The third and final component of effective coaching is 'coaching contexts', which refers to the unique settings in which coaches work. Côté & Gilbert (2009) describe coaching effectiveness and expertise as context specific, with three classifications identified: (1) recreational, (2) developmental and (3) elite sport. Further to this, the following situational factors should be considered: (1) context (individual athlete or team sport, male or female, senior or youth populations), (2) employment type (full or part time), (3) the role (senior position or intern) and (4) the employer (amateur/professional organization, state funded or education). The context alters the focus and attention of the coach and requires a high level of specificity related to programme design and delivery. For example, an S&C coach working with a developmental team athlete with a low training age will plan, deliver and evaluate outcomes differently than if working with an elite individual athlete in a highly demanding performance environment.

SCIENCE OF COACHING

It is still common to hear coaching being referred to as an 'art' as opposed to a science. However, there is an emerging body of research surrounding

motor behaviour and skill acquisition, which scientifically underpins the use of effective communication in coaching. The primary emphasis of such research has been to examine the effects of coaching instructions, cues and feedback on attentional focus (i.e., the conscious ability to focus attention through explicit thoughts in an effort to execute a task). These studies generally reveal that communication or cues that focus the athlete's attention internally on to bodily movements (e.g. extend your knee and ankle) evoke different results to those that cause the athlete to have an external focus (e.g. explode off the ground like a rocket). In general, providing external attentional focus results in increased ability to learn (Wulf et al., 2002), greater retention of information (Wulf, 2007) and enhanced ability to perform tasks under pressure (Bell and Hardy, 2009). In addition to motor learning outcomes, external focus instructions and cues can have positive effects on neuromuscular, physiological and psychophysical outcomes (Benz et al., 2016). Therefore, subtle differences in the way a coach communicates instructions and feedback noticeably impact the athlete's performance, in both the short and long term. Such research provides evidence that coaching is not only an art, but embodies scientific principles, giving the term coaching science legitimacy within the coaching community.

THE SCIENTIST

It is clear from criteria detailed in job specifications that the responsibilities of an S&C coach have evolved to include roles from other sport science disciplines. Before exploring the application of sport science we consider the definition of science:

> Science is the "pursuit and application of knowledge and understanding, following systematic methodologies based on evidence"
>
> (sciencecouncil.org)

Therefore, sport science can be thought of as a scientific process used to guide the practice of sport with the ultimate aim of improving sporting performance (Bishop et al., 2006). The British Association of Sport and Exercise Sciences (BASES) recognizes that the application of scientific

principles in sport is principally achieved through one of the three branches of science: biomechanics, physiology and psychology (see Table 1.1). The importance of nutrition in sport and exercise science is evident and now recognized as an integral role within the interdisciplinary team, hence its inclusion in this chapter. The discipline of S&C is fundamentally engrained in sport science with, for example, the knowledge of programming being underpinned by the understanding of how the anatomy will adapt (physiology), how changing exercise technique can impact the kinetic chain and joint loading (biomechanics), goal setting and motivation (psychology) and advising an athlete what and when to eat to maximize performance or recovery (nutrition). However, in addition to the underpinning knowledge that allows S&C professionals to perform their primary role, coaches are progressively being expected to perform postural, gait and movement screening, testing using laboratory based equipment (e.g. force plates, isokinetic dynamometry, body composition analysis) and monitoring of physical and physiological responses (e.g. vertical jumps, heart rate, position [via GPS], rating of perceived exertion [RPE], subjective questionnaires, blood and saliva analyses).

TABLE 1.1 The definition and correspondence of scientific area to the roles of a typical S&C coach (http://www.bases.org.uk/About-Sport-And-Exercise-Science)

	Definition	*Relation to S&C*
Biomechanics	An examination of the causes and consequences of human movement	– Movement analysis – Athlete performance testing/profiling – Monitoring external training responses
Physiology	An examination of the way the body responds to exercise and training	– Athlete performance testing/profiling – Monitoring internal training responses – Recovery modalities
Psychology	An examination of human behavior within exercise science	– Profiling – Monitoring (questionnaires, e.g., POMS) – Goal setting
Nutrition	An examination and practice of nutrition to enhance wellbeing and athletic performance	– Fueling – Hydration – Supplementation

While the availability of sport science support is increasing, funding to provide such specialist support is still relatively limited for many sports (Reid et al., 2004) and is often reserved for the elite and wealthy organizations. Although it should be noted that it is not suggested that S&C coaches will or should fill the roles of biomechanists, physiologists, psychologists or nutritionists, S&C coaches are expected to have a working understanding of, or at times even embrace the role of these professions. In effect, the role of an S&C coach is similar to that of an interdisciplinary sport and exercise scientist who attempts to utilize and integrate more than one area of sport science to solve real world problems (Burwitz et al., 1994). With the majority of S&C coaches holding a minimum of an undergraduate level degree in an exercise science discipline such as sport and exercise science (Hartshorn et al., 2016), it is perhaps unsurprising as to why the professional S&C coach is expected to absorb these roles. It is also hard to say whether these growing responsibilities were academia led (noting that degrees in S&C teach would-be coaches these skills as though they are required to succeed), or a reflection of the economic status of the organization.

In addition to having sound professional knowledge of a broad range of scientific areas and their practical application, the S&C coach is commonly expected to perform data analysis. Due to the evidence-based environments in which S&C coaches work, the ability to run statistical analyses using appropriate platforms (Excel, SPSS, etc.), is becoming increasingly important. Such skills enable the S&C coach to identify the success or failure of an intervention, to recognize *meaningful* changes and trends and that ultimately inform best practice. Furthermore, this information must be interpreted, filtered and communicated to technical coaches, support staff, athletes and parents in a way that is relevant and meaningful. This requires the S&C coach to firstly, be competent at completing the required analysis and secondly, have adequate interpersonal knowledge to communicate the results within the correct sporting context.

PERFORMANCE LIFESTYLE: NON-CONTACT COACHING

Since the dawn of professionalization in elite sport, and the subsequent increased commercial attention and financial incentives (for both athlete and organization), performance outcomes (success of team/individual, win/loss ratio, player development) have become of paramount importance. Nurturing an athlete is now far detached from the traditional ideology that the individual need only focus on technical/tactical refinement and physical enhancement, all of which can be achieved during training sessions. It is now expected that professionals such as S&C coaches influence lifestyle through the education of athletes to capitalize on the non-contact hours that were once unaccounted for; in essence, there is now a need for non-contact coaching. A term that embraces this concept is 'marginal gains', which was coined and popularized by Sir Dave Brailsford who experienced great success as the performance director of GB Cycling at the 2012 Olympics. Marginal gains refer to the aggregation of a number of small gains that result in a large gain in overall performance. Brailsford sums it up as "put simply… how small improvements in a number of different aspects of what we do can have a huge impact on the performance of the team" (Slater, 2012). Clive Woodward describes using a similar concept when leading the England Rugby team to World Cup victory in 2003. Woodward employed a strategy of improving 'critical non-essentials' (CNe). This approach focused on improving the small details of everything in the preparation and playing of the team. It is worth noting, however, that many athletes need to focus on the development of the basics first, and that such approaches as those mentioned above should be used with highly developed athletes only.

Although many of the approaches used within elite sport are outside the control of S&C coaches (for example, development of technology, organizational culture, competition schedule, travel arrangements, etc.), many alterations to daily lifestyle can be prescribed or controlled, these may include: recovery modalities, sleep hygiene, strategies to reduce risk of infection, ergonomics of equipment and travel, dealing with travelling across time zones, etc. All of the aforementioned are concepts rooted in scientific rationale and are designed and implemented to gain small advantages. The S&C coach must now be constantly investigating ways to improve physical outcomes, positive psychology, training environment and performance lifestyle for athletes to truly gain a competitive edge. However, although slight advantages can be achieved via small modifications, these are only meaningful if the S&C coach has successfully

implemented key concepts, such as appropriate analysis, planning, coaching, monitoring and recovery.

CONSIDERATIONS FOR A MODERN DAY S&C COACH

An S&C coach must consider a multitude of factors before commencing a working relationship with an athlete. Crudely, these can be categorized into: analysis, planning, coaching, monitoring and recovery (before returning back to analysis) (see Figure 1.1). Below is a non-exhaustive list of some of the elements that may need to be considered when working with athletes:

Analysis (& re-analysis)

- *Athlete Background/Objective:* short, medium, long term objectives? How to monitor success or failure? Injury history? Training age? Biological age? Preferences?
- *Sport/Competition Demands:* How many games/tournaments? Priority games/tournaments? How long is the season? Travel demands? Physical demands (how far and fast, etc.)? Injury prevalence within sport/population, including common mechanisms of injury?
- *Postural and Movement Screening:* What type of movement screen? For what reason are you screening? What are the movement dysfunctions? What drives movement dysfunction? Implications on transfer of force through the kinetic chain and injury prevalence?
- *Physical Performance Testing:* Determining successful athletic factors in the sport? Strength/power/speed/agility/endurance tests? Laboratory or field based testing? Reliability? Validity of test? How to interpret and present results?

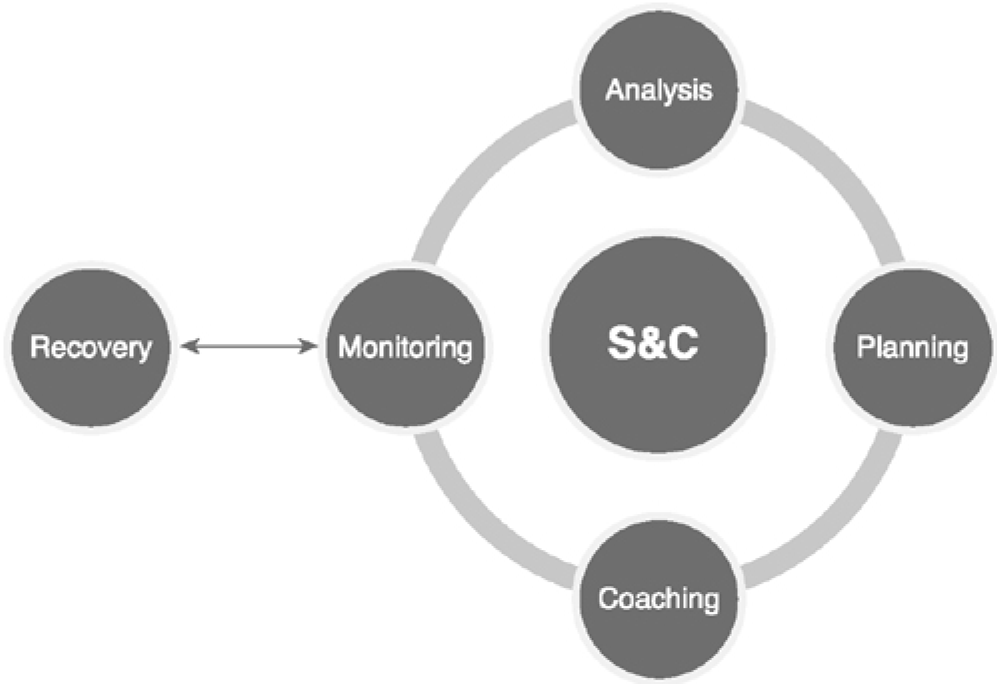

FIGURE 1.1 Considerations for a modern day S&C coach before commencing a working relationship with an athlete.

Planning (within context)

- *Periodization:* Linear or non-linear? How to structure macro, meso and micro cycles? Knowing when to overload and when to taper and when to rest? How to structure technical sessions?
- *Exercise Programming:* Training methods? Associated adaptations? Exercise selection? Exercise sequence (concurrent or single stimulus)? Prescription of training loads?
- *Rehabilitation/Prehabilitation:* Methods and exercises to tackle high risk groups/muscles/joints? When to apply prehabilitation strategies? Return to play/competition strategies? Remedial/preparatory exercise?
- *Non-Contact Coaching:* Nutritional guidance? Sleep hygiene? Strategies to reduce the risk of infection? How to prepare for different time zones, climates, surfaces?

Coaching

- *Professional Knowledge:* How to apply fundamental training principles? Dynamic correspondence of training? Understanding of

sport/competition rules, regulations and physical demands? Knowledge of skill acquisition and pedagogical theory? Which method of training and coaching style induces optimal physical and psychological response (might be different at different times)?

- *Interpersonal Knowledge:* How do you communicate with athletes, coaches and other stakeholders? Awareness of verbal cues (internal vs. external) and non-verbal communication? How do athletes best retain information? Are you able to adapt the programme in relation to how the athlete is feeling?
- *Intrapersonal Knowledge:* Do you evaluate sessions? How do you evaluate? Does it inform future practice? Open and willing to try new ideas?
- *Confidence, Connection, Character:* Do you understand what motivates your athlete/s? How to install confidence? How to be a role model and leader? How can you install good habits that transfer into wider society? How to create a performance environment?

Monitoring

- *Monitor training load (TL) and responses to TL:* Internal methods? External methods? Methods to assess response to training? Performance tests? Physiological markers? Psychological assessments? Wellbeing? Are the metrics/markers/questions sensitive enough to detect meaningful changes? Determining differences between functional overreaching (FO), non-functional overreaching (NFO), overtraining (OT)? Data analysis – reliability? Validity? Statistical significance/meaningful changes (magnitude based inferences)? What, how and who to report the information? What actions are required as a result?

Recovery

- Do we need to use recovery strategies at this point? What is the aim of recovery strategy? What are the best strategies? When to apply? Should everyone use the same recovery strategy? Are they proactively planned or reactive to environment? Physiological and psycho-social response?

(Return to analysis.)

CONCLUSION

S&C is a relatively new support service within the interdisciplinary team in elite sport. It is clear that the role of an S&C professional is multifaceted (see Figure 1.2) and fundamentally requires effective attitudes, behaviours and skills of coaching and the understanding and application of various sport science disciplines to be successful. Kraemer (1990) recognizes additional skills such as organization, administration, athlete motivation, education and public relations as integral to the role. Although traditionally a coach may value professional knowledge above all else, high levels of interpersonal knowledge within sport-specific contexts is essential to be able to constantly interact with athletes, coaches, support staff and other stakeholders. In an era where millions of pounds are at stake and the difference between being on and off the podium are separated by mere fractions of a second, a largely evidence-based culture has evolved. S&C coaches must analyse, interpret and influence decision-making using facts and figures, as hunches or instincts are becoming increasingly more difficult to justify to technical coaches and managers, and can rarely promote change when change is needed. Thus in summary, the discipline of S&C requires the individual to be both an effective coach and an interdisciplinary sport scientist. These required skill sets should be embraced and seen as essential if the S&C coach is to truly excel. Therefore, due to the breadth and depth of knowledge and skills required, it may be suggested that S&C coaches should strive to be excellent 'generalists' and only consider being a 'specialist' once the basics have been mastered. The following chapters provide a greater in-depth analysis of these areas and are an important part of appreciating the role of the modern day S&C coach. These chapters will be principally structured into two sections: (1) an objective and concise review of pertinent literature in the specific subject area, and (2) a discussion (including applied examples) of context-specific practical applications.

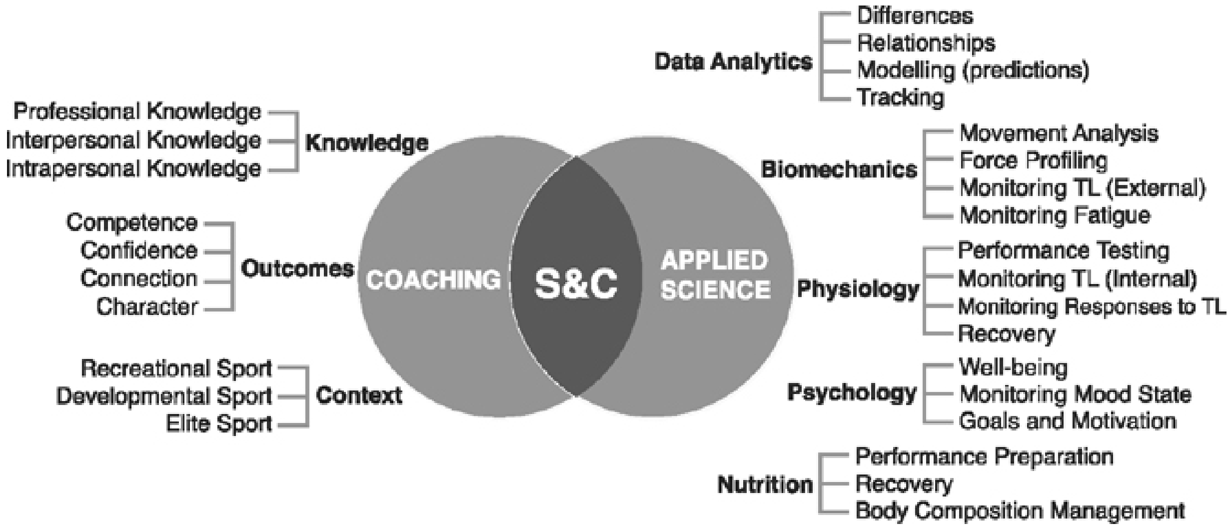

FIGURE 1.2 The multi-faceted nature of strength and conditioning.

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PART 1

Developing your athlete

CHAPTER 2

Developing muscular strength and power

Timothy J. Suchomel and Paul Comfort

INTRODUCTION

This chapter discusses the importance of muscular strength and power with regard to sport performance, physiological underpinnings, and various methods of improving these qualities in athletes. While basic concepts of periodisation and programming for improving strength and power characteristics will be mentioned within this chapter, more thorough discussions can be found in Chapter 8, as well as Bompa and Haff (2009), DeWeese et al. (2015a, 2015b), and Stone et al. (1982).

SECTION 1

THE IMPORTANCE OF MUSCULAR STRENGTH AND POWER FOR ATHLETES

Muscular strength is defined as the ability to exert force on an external resistance (Stone, 1993). Based on the demands of a sport/event, an athlete may have to manipulate their own body mass against gravity (e.g. sprinting, gymnastics, etc.), both their body mass and an opponent's body mass (e.g. rugby, wrestling, etc.), or an external object (e.g. soccer, weightlifting, etc.). Ultimately, the force exerted will change or tend to change the motion of a body in space. This concept is based on Newton's second law (i.e. law of acceleration) whereby force (f) is equal to the product of mass (m) and acceleration (a) (f = ma). Based on this principle, the acceleration of a given mass is directly proportional, and in the same direction of, the force applied. Thus, it appears that muscular strength is the primary factor for producing an effective and efficient movement of an athlete's body or an external object. This concept has been supported throughout the literature as muscular strength has been correlated to greater rate of force development (RFD), power, jumping, sprinting, change of direction, sport-specific skills, and postactivation potentiation (PAP) magnitude (Suchomel et al., 2016b).

Previous literature indicated that both RFD and power output are two of the most important characteristics regarding an athlete's performance (Baker, 2001b; Stone et al., 2002; Morrissey et al., 1995). Given that muscular strength serves as the foundation upon which other abilities can be enhanced, it should come as no surprise that greater magnitudes of RFD and power output are by-products of increased strength.

Rate of force development

Rate of force development may be defined as the change in force divided by the change in time. Regarding sport performance, the ability to rapidly produce force is critical given the time constraints of various tasks. This notion is supported by evidence that suggests that it takes individuals a longer period of time (>300ms) to produce their maximum force (Aagaard et al., 2002a; Aagaard, 2003) compared to the duration of jumping and

ground contact time during sprinting (Andersen and Aagaard, 2006). As mentioned above, increases in muscular strength enhance an athlete's ability to increase their force magnitude and RFD. Previous research has demonstrated that resistance training may enhance an athlete's RFD characteristics, which may lead to improved performance (Aagaard et al., 2002a; Andersen et al., 2010; Häkkinen et al., 1985). A recent review provided evidence that RFD, along with greater muscular strength, may underpin the development of greater power output (Taber et al., 2016) (Figure 2.1).

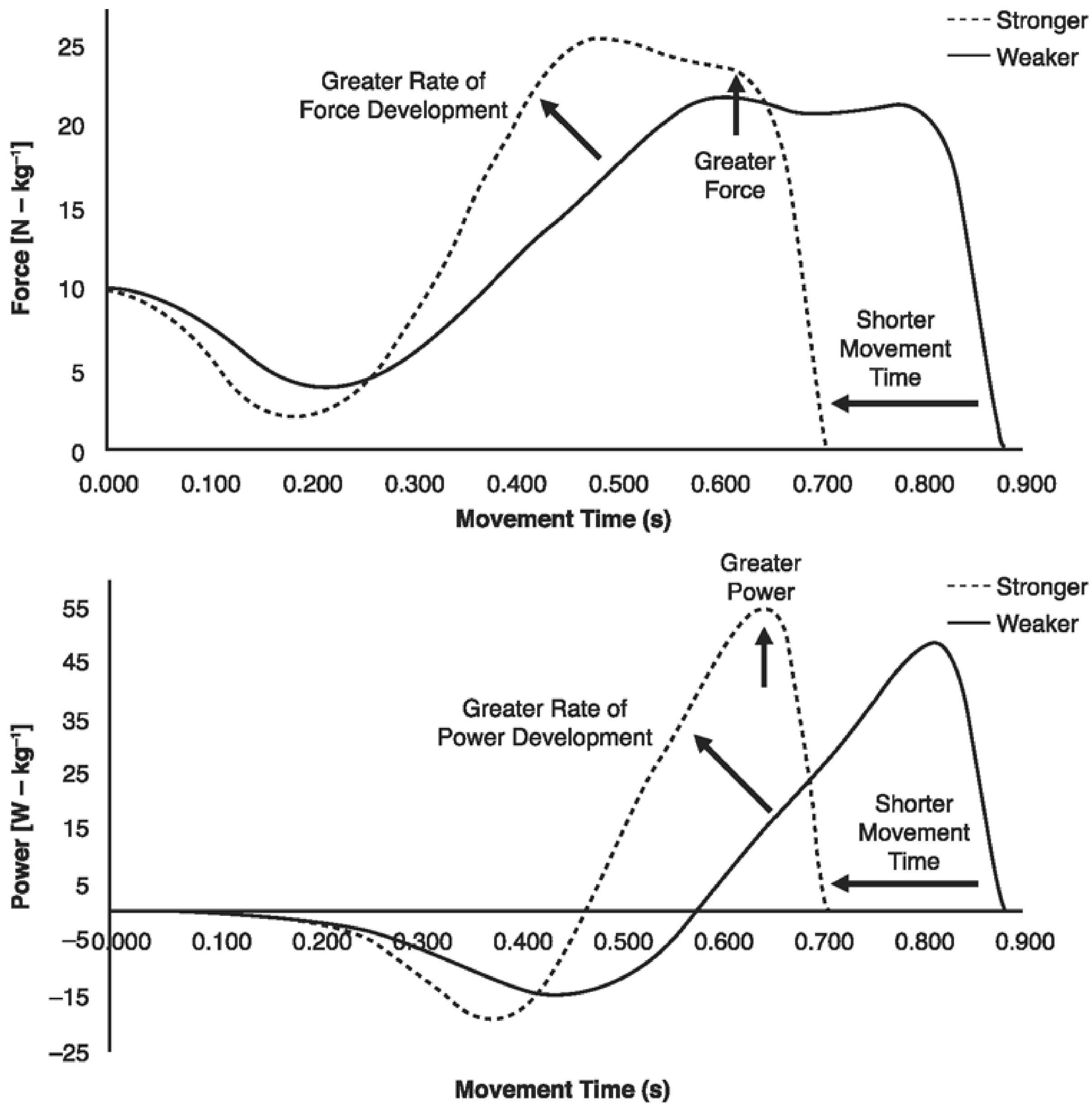
Power output

As mentioned above, alongside RFD, power output is considered to be one of the most important characteristics regarding an athlete's performance. Power output may be defined as the rate of work performed. Any given sport task requires the completion of a given amount of mechanical work. While the work performed is important, athletes have limited time to perform these tasks and thus it would seem beneficial to complete the work as fast as possible. For example, an athlete who completes the required work of a given task more quickly may be given a competitive edge compared to their opponent (e.g. rebound in basketball) or may win the overall competition (e.g. 100m sprint). Previous research has indicated that power output differs between the playing level of athletes (Fry and Kraemer, 1991; Baker, 2001a; Hansen et al., 2011) and between starters and non-starters in various sports (Young et al., 2005; Fry and Kraemer, 1991; Gabbett, 2009). Further research has noted strong relationships between power output and performance characteristics such as sprinting (Weyand et al., 2010; Weyand et al., 2000), jumping (Hori et al., 2008; Newton et al., 1999), change of direction (Nimphius et al., 2010; Spiteri et al., 2012), and throwing velocity (McEvoy and Newton, 1998; Marques et al., 2011). Given the importance of power output to an athlete's success, many strength and conditioning practitioners have sought to improve these qualities through various training strategies. Common training strategies that have been used to enhance power output will be discussed in second half of this chapter.

MORPHOLOGICAL FACTORS AFFECTING STRENGTH AND POWER

Cross-sectional area

Previous literature has indicated that an increase in an athlete's muscle cross-sectional area (CSA) and work capacity (i.e. force production capacity) may lead to an enhanced ability to increase their muscular strength (Minetti, 2002; Zamparo et al., 2002; Stone et al., 1982). Typically, this is achieved via a resistance training phase that includes a high volume of work completed with moderate to moderately high intensities (60–80% 1RM). Greater detail will be provided in second half of this chapter.



Jump Performance Variables					
Subject	Relative Squat Strength (kg.kg^{-1})	Peak Concentric Force (N.kg^{-1})	Peak Concentric Power (W.kg^{-1})	Eccentric RFD (N.kg.s^{-1})	Movement Time (s)
Stronger	2.10	26.16 ± 2.08	55.44 ± 4.19	83.70 ± 31.05	0.707 ± 0.042
Weaker	1.65	26.66 ± 1.87	49.07 ± 3.66	47.11 ± 17.41	0.881 ± 0.122

FIGURE 2.1 Comparison of force, power, RFD and movement time between stronger and weaker athletes during a countermovement jump.

An increase in muscle fibre CSA results in an increased size of the overall muscle (hypertrophy). From a physiological perspective, increases in muscle CSA lead to improved force production due to an increased

number of newly formed sarcomeres. Simply put, an increase in the number of sarcomeres (i.e. smallest contractile unit within muscle cell) increases the number of potential interactions between actin and myosin microfilaments (i.e. cross-bridges) which ultimately increases the force a muscle can produce. This is supported by research from Kawakami et al. (1993) which indicated that muscle fibre pennation angles are greater in hypertrophied muscles. A greater pennation angle permits a greater number of cross-bridge interactions to occur within a given area of the muscle, due to the packing of muscle fascicles within the area (Figure 2.2).

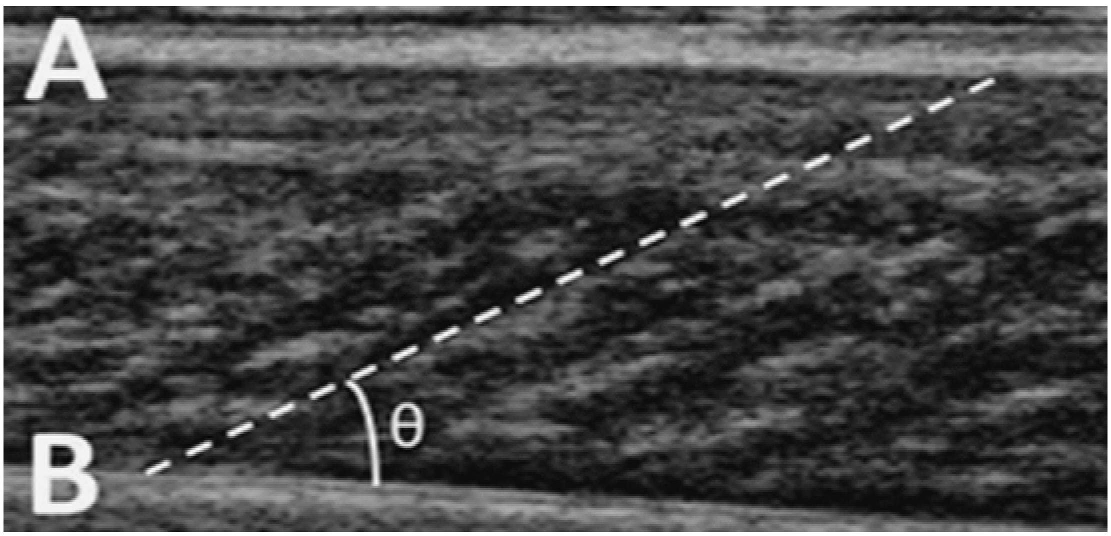


FIGURE 2.2 Medial gastrocnemius (MG) fascicle length (dashed line) and MG pennation angle (θ), as measured between the superficial (A) and deep (B) MG aponeuroses.

Another influence on the CSA of muscle fibres is the ratio of Type II:I fibres. Previous research indicated that an increased CSA following resistance training coincided with a greater Type II:I ratio due to a greater rate of hypertrophy of Type II muscle fibres compared to Type I fibres (Campos et al., 2002). Additional research noted that a greater percent change in Type II:I ratio following eight weeks of resistance training strongly correlated with the percent change of squat jump power (Häkkinen et al., 1981). Thus, it appears that an increased CSA coinciding with a greater Type II:I ratio may increase the ability to generate power by altering the force-velocity characteristics of the muscle. However, it should be noted that the training modality will greatly impact which motor units will be recruited and thus affect which muscle fibres (e.g. Type I, IIa, IIx) adapt to the training stimulus.

The training modality may also affect how additional sarcomeres are added. For example, high force training (i.e. resistance training) may result in increases in a muscle's CSA by adding sarcomeres in parallel (Figure 2.3), which may increase the overall force produced by the muscle given that each sarcomere acts independently. In contrast, high velocity training, e.g., plyometrics (discussed in detail in Chapter 16), may add sarcomeres in series (Figure 2.4), which may increase shortening velocity at the expense of force production given that the sarcomeres in series pull against each other. This concept is important to consider given the demands of athletes in various sports.

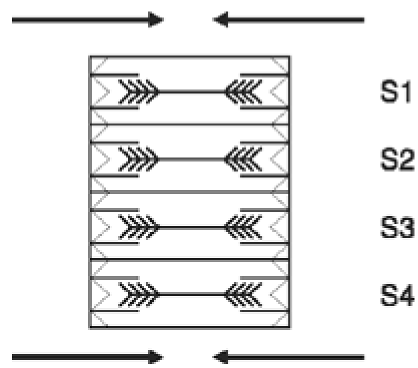


FIGURE 2.3 Four sarcomeres in parallel. Adapted from Stone et al. (2007).

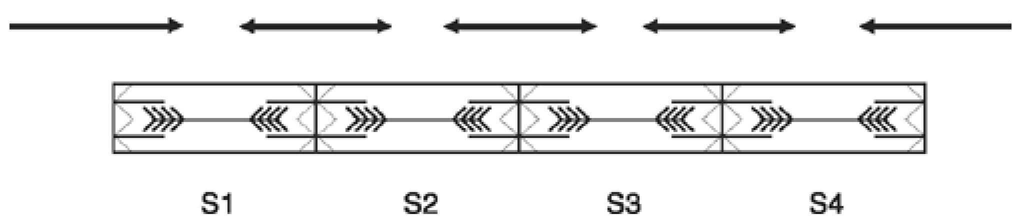


FIGURE 2.4 Four sarcomeres in series. Adapted from Stone et al. (2007).

Muscle architecture

While the overall size of the muscle may affect the magnitude of force produced, additional muscle architecture characteristics may affect muscle tension. A muscle's pennation angle may be defined as the angle in which the fascicles (i.e. bundle of muscle fibres) attach to the superficial or deep aponeurosis (Figure 2.2). The muscle's pennation angle will determine the force-velocity characteristics of the muscle. For example, a greater pennation angle will allow the muscle to place a greater emphasis on force

due to the ability to pack more muscle fascicles into a given area, leading to a greater number of cross-bridge interactions and enhanced force production (Huxley, 1974). In contrast, a smaller pennation angle will place a greater emphasis on velocity due to the position of the fascicles being more parallel in relation to the muscle's aponeuroses, leading to a greater shortening velocity due to the combined shortening of sarcomeres across the area of the muscle belly.

A number of studies have assessed longitudinal changes in muscle architecture (i.e. muscle thickness, pennation angle, and fascicle length) following various resistance training programs, illustrating that changes in muscle architecture may affect performance outcomes. For example, Nimphius et al. (2012) indicated that moderate increases in fascicle length following resistance training were strongly correlated with sprint times to first and second base from home plate in elite softball players. Additional research observed increases in muscle thickness and pennation angles following heavy strength training (Aagaard et al., 2001; Kawakami et al., 1995). Such adaptations may be favorable when it comes to producing greater overall magnitudes of force within the muscle. Further research indicated that training with relatively high velocity muscle actions and lighter loads (<60% 1RM) may produce increases in fascicle length with no changes in pennation angle (Blazevich et al., 2003; Alegre et al., 2006). From a practical standpoint, architectural changes of this nature may increase the overall shortening velocity of the muscle, likely leading to greater increases in power output. Based on previous literature, it appears that muscle architectural changes may be specific to the muscle actions performed (Table 2.1). Additional research comparing eccentric and concentric muscle action training supports this notion (Franchi et al., 2014; Blazevich et al., 2007).

TABLE 2.1 Architectural adaptations in response to different training stimuli

Training Stimulus	CSA	Pennation Angle	Fascicle Length	Fascicle Thickness	↑ Sarcomeres in Series	↑ Sarcomeres in Parallel
Hypertrophy	↑	↑	↓	↑	No	Yes
Strength	↑	↑	↓	↑	No	Yes
Power	–	↓	↑	–	Yes	No
Eccentric Focus	–	↓	↑	–	Yes	No

Notes: CSA = cross-sectional area, ↑ = increase, ↓ = decrease, – = minimal change

It should be noted that the changes in muscle size and pennation angle may not be uniform throughout an entire muscle belly (Ema et al., 2013; Wells et al., 2014). Given the demands of various sport tasks, non-uniform hypertrophy may result in greater growth proximally or distally depending on the activation of musculature during training (Wakahara et al., 2012). For example, the quadriceps muscles of track and field sprinters may hypertrophy more proximally than track cyclists due to the lower limb mechanics required. This idea becomes important when selecting exercises with the intent of increasing the probability that training-induced adaptations will transfer to an athlete’s performance.

NEUROMUSCULAR FACTORS AFFECTING STRENGTH AND POWER

Motor unit recruitment

A motor unit may be defined as an alpha motor neuron and all of the muscle fibres it innervates. The magnitude and rate of force produced coincides with the number and type of motor units recruited. Classic work from Henneman and colleagues (1965) indicates that motor units are recruited in a sequenced manner based on their size (Henneman’s size principle). Motor units are recruited in order from smallest to largest based on the neuromuscular requirements of the activity. For example, smaller motor units that include slow-twitch Type I fibres are recruited at low force magnitudes and are followed by larger motor units that include fast-twitch Type IIa and IIx fibres if higher force and rate of force magnitudes are

required. While the size principle appears to hold true during slow, graded actions as well as isometric (Milner-Brown and Stein, 1975) and ballistic actions (Desmedt and Godaux, 1977; Desmedt and Godaux, 1978), it should be noted that motor unit recruitment thresholds may be lowered during ballistic-type movements due to a greater RFD demand (van Cutsem et al., 1998). Thus, the ability to recruit high-threshold motor units during training would be beneficial to the improvement of muscular strength, RFD, and power.

In order for a motor unit to be trained, it must be recruited. As mentioned above, the nature of the activity will directly affect what motor units are recruited and how they will respond to training. For example, a distance runner repeatedly recruits low-threshold, slow fatiguing (Type I) motor units due to the low-moderate forces that are produced during each stride. Due to the nature of the task, high-threshold (Type II) motor units may not need to be recruited until the Type I motor units fatigue and additional force production is needed to sustain the activity. In contrast, weightlifters performing the snatch require high magnitudes and rates of force production during a task that lasts less than five seconds. In this case, both low- and high-threshold motor units are recruited due to the order of recruitment. However, it would appear that the preferential recruitment of high-threshold motor units would be beneficial for the weightlifter in order to enhance muscular power (Duchateau and Hainaut, 2003; Kraemer et al., 1996). Seminal work by van Cutsem et al. (1998) demonstrated that while the orderly recruitment of motor units existed during both slow, ramp, and ballistic actions following ballistic-type training, motor units were recruited at lower force thresholds. From a practical standpoint, it would appear that training modalities that are ballistic in nature will allow recruitment of larger, Type II motor units at lower thresholds, thus allowing for positive strength and power adaptations to occur.

Firing frequency (rate coding)

Firing frequency may be defined as the frequency at which neural impulses are transmitted from the α-motoneuron to the muscle fibres of recruited motor units. Following the recruitment of specific motor units, force production properties may be modified in two ways by the firing frequency. Previous literature suggests that force production magnitude may increase

upwards to 300–1500% when the firing frequency of recruited motor units increases from its minimum to its maximum (Enoka, 1995). In addition, RFD may be impacted by the firing frequency of motor units due to high initial firing frequencies being linked to an increase in doublet discharges (i.e. two consecutive motor unit discharges in ≤ 5ms) (van Cutsem et al., 1998). Both the increase in magnitude and RFD as the result of an increased firing frequency may ultimately contribute positive strength and power adaptations. Practically speaking, certain training modalities may lead to improvements in the firing frequency of recruited motor units. Previous research has demonstrated that ballistic-type training may enhance motor unit firing frequency within 12 weeks (van Cutsem et al., 1998). Additional literature suggests that other ballistic training modalities such as weightlifting movements (Leong et al., 1999) and sprinting (Saplinskas et al., 1980) may enhance motor unit firing frequency, leading to enhanced strength-power characteristics.

Motor unit synchronisation

Motor unit synchronisation refers to the simultaneous activation of two or more motor units resulting in increased force production. While the physiological underpinnings are not fully understood, some literature indicates that motor unit synchronisation is more related to RFD compared to the magnitude of force produced (Semmler, 2002). Milner-Brown and Stein (1975) indicated that six weeks of strength training led to an increase in motor unit synchronisation. Another study indicated that the motor unit synchronisation strength was the largest in the dominant and non-dominant hands of the weightlifters compared to musicians and untrained individuals (Semmler and Nordstrom, 1998). Although van Cutsem et al. (1998) found that motor unit synchronisation did not appear to change following ballistic-type training, another study indicated that motor unit synchronisation was enhanced during tasks that require movement, especially those involving rapid muscle actions (Semmler et al., 2000). Finally, Aagaard et al. (2000) suggested that heavy strength training may result in an increase in motor unit synchronisation, possibly contributing to force production.

Neuromuscular inhibition

Neuromuscular inhibition, which refers to a reduction in the voluntary neural drive of a given muscle group during voluntary muscle actions, may negatively affect force production due to neural feedback received from muscle and joint receptors (Gabriel et al., 2006). Undoubtedly, neural mechanisms that negatively affect the development of force and power may alter potential adaptations. However, Aagaard et al. (2000) indicated that heavy strength training may down-regulate Ib afferent feedback to the spinal motoneuron pool, ultimately reducing neuromuscular inhibition and increasing force production. Additional studies reported an enhanced neural drive from the spinal and supraspinal levels following strength training that coincided with a decrease in neuromuscular inhibition (Aagaard et al., 2002b) and enhanced RFD (Aagaard et al., 2002a). Taking the above into account, heavy resistance training may lead to an enhanced neural drive, increased RFD, and decreased neuromuscular inhibition, leading to potential enhancements in the strength-power characteristics of athletes.

SECTION 2

TRAINING CONSIDERATIONS FOR IMPROVING MUSCULAR STRENGTH AND POWER

In addition to understanding the physiological underpinnings that affect both strength and power, practitioners must select a periodisation model, exercises and/or training modalities, the movement intent (i.e. ballistic or non-ballistic), and loads for each exercise, all while implementing each factor in a sequenced progression. Moreover, the athlete's training status must be considered as certain training methods may be more appropriate for those who are more/less well trained. Readers are directed to Cormie et al. (2011) for an additional review on developing neuromuscular power.

PERIODISATION MODEL

An abundance of periodisation models exist within the strength and conditioning field. Much of the extant literature supports the notion that block periodisation may provide superior results compared to other models, as discussed by DeWeese and colleagues (2015a). This model is based on the idea that a concentrated load may be used to train one specific characteristic during each training phase, while maintaining the previously developed characteristic(s) (Figure 2.5). This appears to be advantageous considering that previous literature has indicated that it may be difficult, and potentially less productive, to develop multiple physiological characteristics or motor abilities simultaneously (Stone et al., 2007; Issurin, 2010; Issurin, 2008). It should be noted that other models of periodisation may still provide an effective blueprint for developing an athlete's strength-power characteristics (e.g. traditional, daily undulating, etc.). However, further research between periodisation models with different athletic populations is still needed to determine their effectiveness. Chapter 8 will discuss the concept of periodisation and the effectiveness of various periodisation models for athletic performance in greater detail.

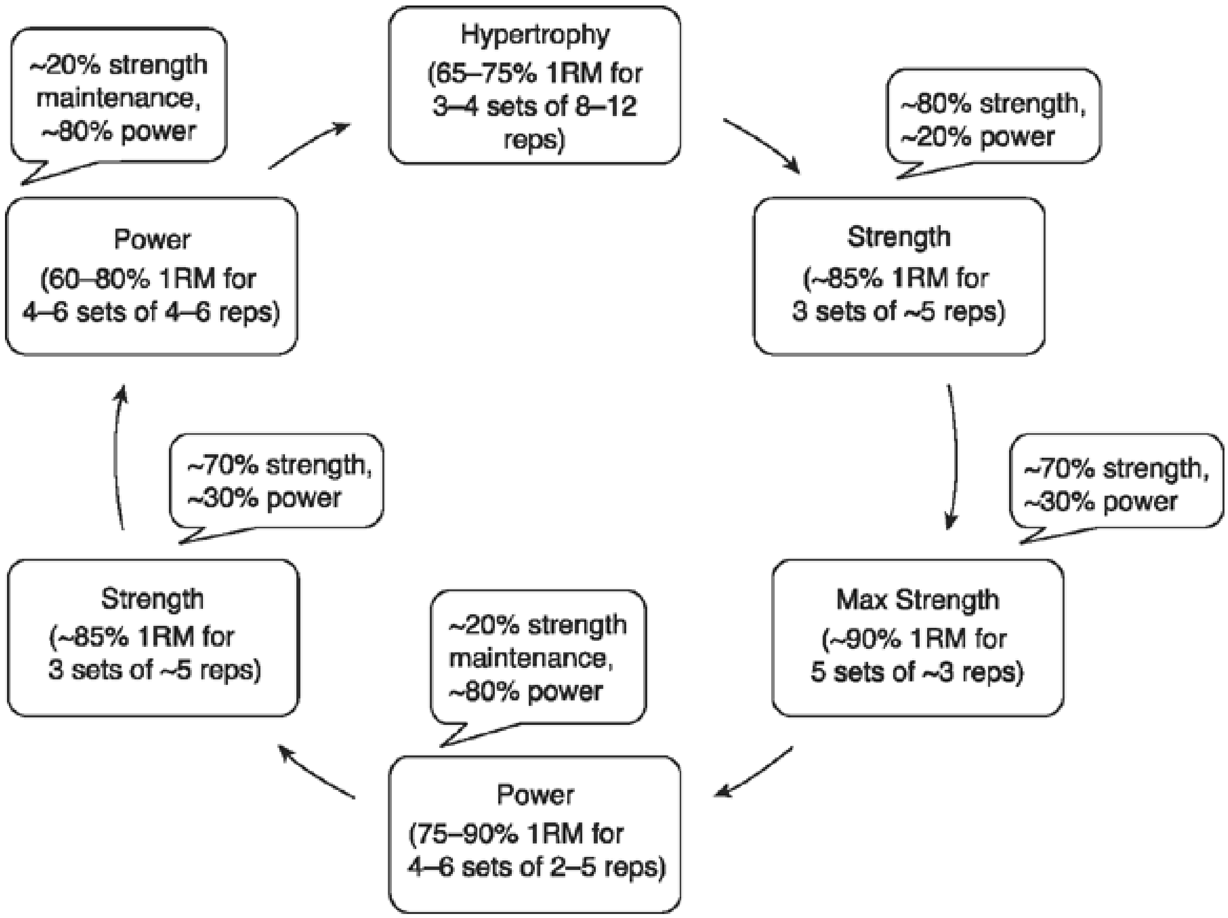


FIGURE 2.5 Example emphasis change during a periodised training programme (phase potentiation).

RESISTANCE TRAINING MODALITIES

The type of training modality may provide a vastly different stimulus that may affect gains in muscle CSA, strength, or power. As discussed in Chapters 8 and 15, the training mode and exercises should be selected based on their ability to achieve the goals of each training phase. For example, exercises may be selected based on their power characteristics. Because power is the product of force and velocity, certain exercises may emphasise one or both characteristics. Simply put, FORCE • velocity, force • VELOCITY, or FORCE • VELOCITY are all combinations of exercise types used in training. Table 2.2 displays relative power outputs ($W.kg^{-1}$) of a variety of exercises discussed within the literature. The following paragraphs discuss various forms of resistance training and their effectiveness at developing muscular strength and power.

TABLE 2.2 Relative power outputs for male athletes during various exercises

Exercise	*Relative power outputs; male* ($W \cdot kg^{-1}$)	*Force-velocity characteristics*
Clean	33–80	High force and high velocity movements
Hang power clean	22–47	
Jerk	44–80	
Jerk drive	28–56	
Power clean	25–80	
Snatch	34–80	
Clean pull from floor	33–80	Moderate–high force and moderate–high velocity movements
Hang high pull	47–54	
Jump shrug	57–70	
Mid–thigh clean pull from dead stop	35–67	
Mid–thigh snatch pull from dead stop	35–48	
Snatch pull from floor	30–80	
Countermovement jump squat	64–75	Low force and high velocity movements
Static jump squat	58–69	
Bench press	0.3–8.3	High force and low velocity movements
Deadlift	11–13	
Squat	11–30	

Notes: The relative power outputs displayed may vary based on the level of the athlete, load lifted, technical efficiency of the athlete, and method used to quantify power output. The data presented represent the ranges of averages across various loads within the literature. Adapted from Comfort et al. (2012; 2015), Cormie et al. (2008), Driss et al. (2001), Garhammer (1980; 1985; 1991; 1993), Haff et al. (1997; 2001; 2012; 2015), Kawamori et al. (2005), McBride et al. (1999), Stone et al. (2008), Suchomel et al. (2013; 2014; 2015), and Thompson et al. (2010).

Bodyweight exercise

Bodyweight exercise is one of the most basic forms of resistance training that has been used for decades. Some of the most common bodyweight exercises, such as bodyweight weight squats, push-ups, pull-ups, and sit-ups, are still implemented in resistance training programs to this day as

either a training or progression exercise. Bodyweight exercises have several advantages including being specific to the individual's anthropometrics and muscle/tendon insertion, the inclusion of closed chain-based exercises, the ability to train multiple muscle groups simultaneously, a focus on improving relative strength, and its accessibility and versatility compared to other training methods (Harrison, 2010).

Like any training method, bodyweight exercise has its limitations. The most obvious limitation of bodyweight exercises is the inability to continue to provide an overload stimulus to the athlete, preventing a significant transfer to absolute strength measures (Harrison, 2010). For example, practitioners may continue to prescribe a greater number of repetitions or modify the movement (e.g. push-up variations including incline, feet elevated, etc.) in order to progress each bodyweight exercise. However, a continual increase in repetitions may lead to the development of strength-endurance characteristics instead of the development of strength-power characteristics necessary for enhanced sport performance. Based on their advantages and limitations, it is suggested that bodyweight exercises should be prescribed to enhance basic strength and movent characteristics before progressing to other training methods that may result in greater strength and power adaptations.

Machine vs. free weight training

When prescribing either machine or free weight exercises, practitioners should note that each method has its limitations. For example, machine-based exercises allow for the isolation of specific muscle groups, which may be important from a rehabilitation standpoint. However, utilising machine-based exercises for sport performance may be questionable. Previous literature indicated that athletic movements rarely include muscle actions performed in an isolated manner (Behm and Anderson, 2006), with the transfer from isolation exercises to athletic performance being somewhat limited (Blackburn and Morrissey, 1998; Augustsson et al., 1998; Östenberg et al., 1998). Thus, it appears that exercises that incorporate multiple muscle groups may provide a superior training alternative (Anderson and Behm, 2005, Bobbert and Van Soest, 1994). Furthermore, it is been noted that free weight exercises may recruit muscle stabilisers to a greater extent than machine-based exercises (Haff, 2000). Collectively, it

appears that the movement similarities with athletic movements and the recruitment of muscle stabilisers of free weight exercises may produce greater strength-power adaptations as they relate to sport performance.

Training with weightlifting movements

As displayed in Table 2.2, weightlifting exercises produce the greatest power outputs compared to other types of exercise. Given the importance of muscular strength and power in sport, it is not surprising that many practitioners implement the weightlifting movements and their derivatives within resistance training programs. Weightlifting movements are unique in that they exploit both the force and velocity aspects of power output by moving moderate-heavy loads with ballistic intent. One key advantage of the ballistic nature is the fact that the athlete aims to accelerate throughout the concentric phase, whereas exercises such as the bench press and squat result in deceleration during the later stages of the concentric phase (Newton et al., 1996; Lake et al., 2012). Previous research has demonstrated that weightlifting movements may provide a superior strength-power training stimulus compared to jump training (Tricoli et al., 2005; Teo et al., 2016), traditional resistance training (Hoffman et al., 2004; Channell and Barfield, 2008; Chaouachi et al., 2014; Arabatzi and Kellis, 2012), and kettlebell training (Otto III et al., 2012). Greater detail regarding the use of weightlifting movements during resistance training will be provided in Chapter 15.

Plyometric training

While a thorough discussion of plyometric exercises will be provided in Chapter 16, this chapter will provide a brief discussion on their effectiveness as a strength-power training stimulus. Plyometric movements may be defined as quick, power movements that utilise a pre-stretch/countermovement that includes the stretch-shortening cycle. Specifically, plyometrics refer to a concentric muscle action that is enhanced by a preceding eccentric muscle action. Their ballistic nature, combined with an emphasis on power development, has led to their use within strength and conditioning programs for athletes. A recent meta-analysis concluded that training with plyometric exercises may produce

similar improvements in vertical jump height compared to training with weightlifting exercises (Hackett et al., 2015), demonstrating that plyometrics may be an effective training stimulus for athletes.

When it comes to designing a plyometric training program, practitioners should consider the fact that plyometric exercises are a form of resistance training and should therefore be periodised. Previous research demonstrated the effectiveness of programming plyometric exercises in a periodised fashion during six week training programs by decreasing the volume of foot contacts and increasing the intensity of the plyometric exercises during the final four weeks of the training (Ebben et al., 2014; Ebben et al., 2010). See Chapter 16 for greater detail regarding plyometric training. Practitioners should also consider the frequency of training sessions, length of the program, and recovery time between repetitions, sets, and training sessions. Typical training frequencies range from 1 to 3 sessions per week, while the length of most programs ranges from 6 to 10 weeks (Allerheiligen and Rogers, 1995).

Most plyometric exercises are implemented using the athlete's body mass as the resistance. However, using only the athlete's body mass as a resistance may be limited in terms of strength-power development. Practitioners may be able to prescribe small additional loads to increase the loading stimulus on the athlete; however a more sensible method would be to increase the plyometric exercise intensity, while simultaneously adjusting the volume to meet the needs of each athlete.

Eccentric training

Eccentric muscle actions are those that lengthen the muscle as a result of a greater force being applied to a muscle than the muscle itself can produce. Although not well understood, eccentric muscle actions possess unique molecular and neural characteristics that may contribute to a variety of adaptations (Douglas et al., 2016b). A recent review indicated that eccentric training may produce similar or greater adaptations in muscle mechanical function (e.g. muscular strength, muscular power, RFD, and stiffness), morphological adaptations (e.g. tendon and muscle fibre CSA), neuromuscular adaptations (e.g. motor unit recruitment and firing frequency), and performance (e.g. vertical jumping, sprint speed, and change of direction) compared to concentric, isometric, and traditional

(eccentric/concentric) training (Douglas et al., 2016a). Due to the potential adaptations listed above, it is not surprising that eccentric exercise has received a growing interest as a training stimulus.

Although interest in utilising eccentric training has grown, little is known about how to best implement this type of training. Previous literature indicated that adaptations from eccentric exercise are based on their intensity (English et al., 2014; Malliaras et al., 2013) and contraction speed (Farthing and Chilibeck, 2003; Isner-Horobeti et al., 2013). Taking this into account, the previously mentioned literature has indicated that heavier eccentric loads may produce favourable adaptations compared to lighter loads. Interestingly, practitioners have the opportunity with eccentric-type training to prescribe loads in excess of what the athlete can lift concentrically (i.e. >1RM).

Another aspect to consider with eccentric training is the type of movement(s) the athlete is able to perform. For example, much of the previously discussed literature within this section has focused on eccentric-only movements. However, a growing body of literature has examined another type of eccentric training, termed accentuated eccentric. Accentuated eccentric training involves performing the eccentric phase of a lift with a heavier load than the concentric phase as a result of a portion of the load being removed by a weight release system (Ojasto and Häkkinen, 2009), spotters (Brandenburg and Docherty, 2002), the athlete dropping it (Sheppard et al., 2008), or flywheel (de Hoyo et al., 2015) at the end of the eccentric phase. Collectively, the previous studies provide evidence that accentuated eccentric training may produce greater adaptations in explosive performance characteristics (i.e. jumping, sprinting, and concentric power). Although a limited body of literature exists, it appears that accentuated eccentric training may provide an effective training stimulus to improve an athlete's strength-power performance.

Complex training & strength-power potentiation complexes

Complex training (CT) is a training modality that involves completing a resistance training exercise prior to performing a ballistic exercise that is biomechanically similar (Robbins, 2005). For example, back squats may be paired with countermovement jumps, while the bench press may be paired with bench press throws. CT may allow athletes to perform high force or

power exercises at a higher intensity compared to traditional training (Verkhoshansky, 1986; Ebben et al., 2000), ultimately creating a superior training stimulus. In theory, CT may result in greater strength and speed adaptations compared to traditional resistance training methods longitudinally by providing a broader range of training stimuli (Ebben and Watts, 1998; Jones and Lees, 2003).

A topic of frequent research that uses CT principles is postactivation potentiation (PAP). PAP is defined as an acute enhancement in performance as a result of the muscle’s contractile history (Robbins, 2005). Training complexes designed to produce a potentiated state are termed strength-power potentiating complexes (SPPCs) (Robbins, 2005; Stone et al., 2008). SPPCs involve performing a high force or high power movement that is used to potentiate the performance of a subsequent high velocity or power movement. While a number of studies have demonstrated that various potentiation stimuli may acutely enhance strength-power performance (Gullich and Schmidtbleicher, 1996; Young et al., 1998; Bullock and Comfort, 2011), a number of factors within the SPPC or the athlete’s characteristics may affect the magnitude of potentiation produced (Suchomel et al., 2016a). Thus, it is not surprising that similar SPPCs resulted in no change or a decrease in subsequent performances in other studies (Tsolakis and Bogdanis, 2011; Jensen and Ebben, 2003; Till and Cooke, 2009). While the concept of implementing SPPCs within an athlete’s resistance training programs is appealing, limited research has examined the longitudinal effects of training with SPPCs (Docherty and Hodgson, 2007). In addition, practitioners should note that the use of SPPCs may not be as appropriate for weaker individuals as greater muscular strength may lead to faster and greater potentiation (Suchomel et al., 2016d; Seitz et al., 2014; Miyamoto et al., 2013). Finally, it should be noted that the long-term use of SPPCs may not be appropriate given the goals of specific resistance training phases. For example, implementing SPPCs may be specific to the goals of a strength-speed phase, but actually counterproductive during a strength-endurance phase.

Unilateral vs. bilateral training

Some practitioners may argue that unilateral exercises may be more sport-specific given the unilateral weight bearing phase of various sport tasks

(e.g. sprinting, cutting tasks, etc.). Thus, a frequent topic of discussion within the strength and conditioning field is the use of unilateral exercises compared to bilateral exercises. Unilateral/partial unilateral movements may be defined as those where the resistance is unevenly distributed between an individual's limbs, whereas bilateral movements are those where the resistance is distributed evenly, for the most part, between an individual's limbs (McCurdy et al., 2005). The vast majority of resistance training programs implement predominantly bilateral exercises for strength and power development. This is not surprising given that strong relationships exist between bilateral strength and sprinting, jump height and peak power, and change of direction performance (Suchomel et al., 2016b). However, in order to provide practitioners with a variety of options for exercise prescription, further discussion on unilateral exercise is needed.

Several studies have compared the training effects of unilateral and bilateral training. McCurdy et al. (2005) examined the strength and power adaptation differences following eight weeks of unilateral or bilateral strength training and plyometric exercise in untrained subjects. Their results indicated that both groups improved to a similar extent, suggesting that either mode of training may be equally as effective. Similar results from another study indicated that both unilateral and bilateral plyometric training improved both countermovement jump (CMJ) and alternate leg bounding performance in previously untrained females (Makaruk et al., 2011). However, the authors also noted that only the bilateral training group retained their training adaptations following a four week detraining period. A more recent study indicated that similar improvements in unilateral and bilateral strength, sprint speed, and agility were displayed by Academy rugby players following five weeks of either training with the rear foot elevated split squat or traditional back squat exercise (Speirs et al., 2016). Collectively, the previous studies indicate that training with unilateral exercises may be an effective alternative to bilateral exercises when it comes to improving various performance parameters.

Previous literature has indicated that gluteus medius, hamstring, and quadriceps activation was greater during a modified split squat compared to a traditional bilateral squat (McCurdy et al., 2010). This should not be overly surprising given the decreased stability of unilateral exercises. However, decreased stability may be viewed as a limitation because it is difficult to prescribe heavy loads with unilateral exercises. Given that

greater stability within a movement may lead to a greater potential to express force (Behm and Anderson, 2006), it would appear that bilateral exercises may serve as a better foundation for improving an athlete’s strength-power characteristics. However, that is not to say that unilateral exercises should not be programmed; rather, they should be implemented as assistance exercises to bilateral lifts, especially during the general preparatory phase of training.

Variable resistance training

Traditional resistance training methods typically involve performing exercises with an eccentric and concentric component in which the external load remains constant throughout the entire range of motion. While this type of training has become an essential addition to training programs, it is not without its limitations. For example, an athlete performing a back squat may be limited at the lowest point of their squat due to a decreased capacity to produce force in that position. As a result, athletes may experience a “sticking point” when they begin to ascend due to mechanical disadvantages being present within the active musculature. In contrast, muscle force production continues to increase and peaks during the top portion of the squat. Based on this description of the back squat, it would appear that a method of training that trains each portion of the lift based on its mechanical advantage/disadvantage would be beneficial.

Variable resistance training refers to a training method that alters the external resistance during the exercise in order to maximize muscle force throughout the range of motion (Fleck and Kraemer, 2014). Traditionally, this method of training involves the use of chains or elastic bands during exercises such as the back squat (Figure 2.6) or bench press (Figure 2.7). The addition of chains or elastic bands may alter the loading profile of an exercise (Israetel et al., 2010), which may allow the athlete to match changes in joint leverage (Zatsiorsky, 1995) and overcome mechanical disadvantages at various joint angles (Ebben and Jensen, 2002; Wallace et al., 2006). Support for this method of training comes from a meta-analysis that indicated that greater strength gains were produced during the bench press exercise following variable resistance training compared to traditional methods (Soria-Gila et al., 2015). While additional training studies are

needed, it appears that variable resistance training may be used as an effective training tool for developing muscular strength and power.

Kettlebell training

Another form of resistance training that has gained popularity is the use of kettlebell exercises. Kettlebells are implements that consist of a weighted ball and handle (Cotter, 2014). Among other movements, individuals have used kettlebells in a variety of ways including swings, goblet squats, accelerated swings, and modified weightlifting exercises such as a snatch for the purposes of developing strength and power. Previous research has indicated that kettlebell training may improve various measures of muscular strength (Otto III et al., 2012; Lake and Lauder, 2012; Jay et al., 2011; Manocchia et al., 2013; Jay et al., 2013) and explosive performance as measured by vertical jumping (Otto III et al., 2012; Lake and Lauder, 2012) and clean and jerk three repetition maximum (RM) (Manocchia et al., 2013). However, it should be noted that two other studies indicated that vertical jump (Jay et al., 2013) and sprint performance (Holmstrup et al., 2016) were not enhanced following kettlebell training when compared to a control group, indicating that not all research supports the use of kettlebells as a strength training modality.

FIGURE 2.6 Back squat exercise using variable resistance with chains.

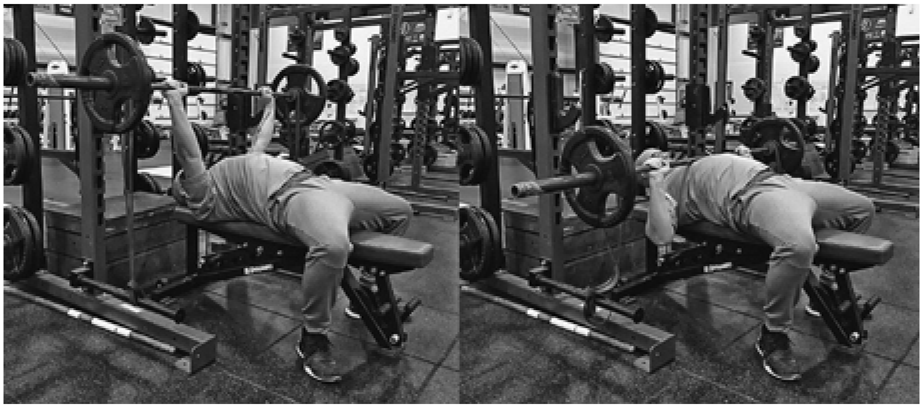


FIGURE 2.7 Bench press exercise using variable resistance with elastic bands.

The majority of available research suggests that kettlebell training may provide an effective strength-power training stimulus. However, it should be noted that more traditional methods of training, such as weightlifting, may provide superior adaptations when it comes to improving maximal strength and explosiveness (Otto III et al., 2012). This may in part be due to overload that may be placed on the body. For example, athletes training with weightlifting movements may be able to clean and jerk 100kg; however, it may be difficult to perform a kettlebell swing with the same load using proper technique. Further research examining kettlebell training is needed to determine its role within strength and conditioning programs.

BALLISTIC VS. NON-BALLISTIC

The intent of performing an exercise may alter a given training stimulus. Ballistic exercises (i.e. those that accelerate throughout the entire concentric movement) may lower the recruitment threshold for motor units (van Cutsem et al., 1998, Desmedt and Godaux, 1977) and allow the entire motor neuron pool to be activated within a few milliseconds (Duchateau and Hainaut, 2003). Based on the discussion provided earlier in this chapter, recruiting a greater number of motor units will ultimately lead to greater magnitudes and rates of force production. This notion is supported by previous research that indicated that ballistic exercises produced greater force, velocity, power, and muscle activation compared to the same exercises performed quickly (Lake et al., 2012, Newton et al., 1996). Additional research indicates that ballistic movements may also produce

superior potentiation effects compared to non-ballistic exercises (Suchomel et al., 2016c). The superiority of ballistic exercises to produce greater training stimuli is displayed in Table 2.2, where the ballistic exercises (e.g. weightlifting movements) produce greater relative power outputs compared to traditional/non-ballistic resistance training exercises (e.g. back squat, bench press, etc.). Due to the potential training benefits of ballistic-type exercises, it should come as no surprise that practitioners often implement these exercises throughout the training year. However, it should be noted that the goals of each training phase will often dictate which exercises are prescribed.

LOADING CONSIDERATIONS

Training to failure

Training with heavy loads will ultimately lead to increases in muscular strength. A method of training that emphasises this idea is training with loads that result in failure on the final repetition. The theory behind this method is that training with RM loads will lead to greater overall adaptations in strength compared to training with submaximal loads. However, a previous meta-analysis indicated that training to failure does not elicit greater strength gains compared to not training to failure (Peterson et al., 2005). This is supported by a second meta-analysis that stated that training to failure may be unnecessary when it comes to maximising muscular strength (Davies et al., 2016). The authors noted that if training to failure is incorporated into training programs, it should be used sparingly in order to limit the risks of injuries and overtraining. While training to failure likely stimulates the recruitment of high threshold motor units, this type of training cannot be sustained for long periods of time. Certainly there are periods where the primary emphasis may be lifting very heavy loads (90–95% 1RM) to improve maximal strength qualities; however, it does not appear that training to failure is a required element in an athlete's resistance training program.

Combining heavy and light loads

Training for maximal strength and power requires the use of a variety of loads. Specific to strength gains, heavier loads will likely provide a training stimulus that will enhance the magnitude and rate of force production of an athlete. In contrast, training to enhance maximal power production requires the use of a range of loads that train the entire force-velocity curve (Haff and Nimphius, 2012). The training loads implemented with various exercises should complement the exercises that are being used. For example, heavier loads may be used with core exercises (e.g. squats, presses, and pulls) and certain weightlifting movements (e.g. power clean, pull from the floor, mid-thigh pull) that emphasise high force production, while lighter loads may be prescribed for more ballistic movements that emphasise high velocities (e.g. jump squat, jump shrug, bench press throws). However, as mentioned above, combination loading may also be achieved through the implementation of both weight training (high force) and plyometrics (high velocity). Suchomel et al. (2017) discussed this concept using weightlifting derivatives.

It should be noted that a combination loading stimulus may also be achieved across each microcycle (e.g. week of training) and session of training. Over the course of an individual microcycle, the same exercises may be implemented throughout the week; however, the exercises are prescribed using a “heavy day/light day” loading concept. A recent review discussed this method of programming for track and field athletes (DeWeese et al., 2015b). In addition, Harris et al. (2000) displayed that a combination loading group performed back squats at 80% 1RM on their heavy day and back squats at 60% 1RM on their light day. Similarly, achieving a combined loading stimulus within a single training session is realised through the combination of working sets as well as warm-up and warm-down sets of each exercise.

Optimal loads

Some literature supports the idea of training at or near the load that maximises power production, termed the “optimal load” (Kawamori & Haff, 2004). In theory, optimal loads provide an ideal combination of force and velocity magnitudes that produce high power outputs. However, it should be noted that a number of factors may affect optimal loads. For example, recent research indicated that the optimal load or range of loads

for the greatest power output is exercise specific for both upper (Soriano et al., 2016) and lower body exercises (Soriano et al., 2015). Additional literature suggests that the load that maximises power may be specific to the system (athlete plus barbell), barbell, or joint (McBride et al., 2011), indicating that it may be necessary to train with a range of loads, especially as an athlete gets stronger (Stone et al., 2003). Collectively, it appears that training near or at optimal loads may be beneficial from a power development standpoint. However, the extant literature supports the notion that practitioners should prescribe a range of loads instead of a single load in order to train both low and high force power characteristics during different exercises (Haff and Nimphius, 2012).

TRAINING STATUS

An athlete's training status may dictate 1) what exercises and loads the individual can tolerate and 2) what their training emphasis should be. As with any type of training, practitioners should be mindful of an athlete's abilities as exercise competency will dictate whether or not it is appropriate to implement certain exercises or progress using various training modalities.

Because muscular strength serves as a foundation for a number of other abilities (Suchomel et al., 2016b), the training emphasis for weaker and/or less well-trained athletes should focus on increasing maximal strength. Too often practitioners place an emphasis on high velocity or power training without developing the necessary strength characteristics that will allow the athletes to exploit power-type training more extensively. That is not to say that power-type exercises such as weightlifting movements and plyometrics should not be prescribed to a weaker athlete, but they may not be featured as exclusively until an athlete increases their baseline strength levels using core movements such as squats, presses, and pulls.

While the emphasis of training for weaker and/or less well-trained individuals may be on gaining maximal strength, the emphasis of training for stronger/well-trained athletes may be modified. Previous literature indicated that although strength influences an athlete's performance, the degree of this influence may diminish when athletes maintain high levels of strength (Kraemer and Newton, 2000). Therefore, the likely magnitude of potential adaptation for increasing strength is reduced as an athlete's

maximal strength increases. As a result, additional literature has indicated that after achieving specific standards of strength (parallel back squat ≥2 x body weight as the barbell load), an athlete's training emphasis may shift towards power-type or RFD training while maintaining or increasing their strength levels (Stone et al., 2007, DeWeese et al., 2015b). Specifically, achieving a high baseline level of strength may allow an athlete to maximize the benefits of incorporating training modalities such as plyometrics, ballistic exercises, and CT.

SUMMARY

Muscular strength is defined as the ability to exert force on an external object and is considered to be the primary factor for greater RFD and power. It is important that adequate strength development is the primary, although not exclusive, focus of training initially, before progressing to power-type training once an athlete's strength increases. By achieving a high level of muscular strength, athletes may increase their RFD, power, and athletic performance, while also decreasing the risk of injury (Suchomel et al., 2016b). Both morphological and neuromuscular factors may affect the development of muscular strength and power. Morphological factors include muscle cross-sectional area and architecture while neuromuscular factors include motor unit recruitment, rate coding, motor unit synchronisation, and neuromuscular inhibition.

From a practical standpoint, the periodisation model, modality of resistance training, prescribed loads, and training status may directly affect muscular strength and power adaptations and training emphases. The training programs of weaker individuals should focus on improving muscular strength before too much emphasis is placed on power. In contrast, stronger athletes may shift to a power emphasis while maintaining or improving their strength level.

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CHAPTER 3

Stretch-shortening cycle and muscle-tendon stiffness

John J. McMahon

INTRODUCTION

This chapter begins by introducing the stretch-shortening cycle (SSC), describing its underpinning mechanisms and explaining the influence of muscle-tendon stiffness (MTS) on SSC function. The chapter then describes the different levels at which MTS can be directly or indirectly measured during SSC tasks which involve the entire lower limb(s) such as running, jumping and hopping. The following section provides a commentary on the effects of MTS on performance outcomes measured during running, jumping and hopping which serves to inform practitioners of the benefits and limitations of performing these tasks with a stiff or compliant limb strategy. The chapter concludes by summarising the results of contemporary training studies to inform training recommendations. The information presented in this chapter should, therefore, help practitioners with the design of their training programmes aimed at developing task-specific SSC function.

WHAT IS THE STRETCH-SHORTENING CYCLE?

Early research findings revealed that when isolated skeletal muscle fibres were tetanically stimulated (i.e., maximally activated by a nerve stimulator), stretched and then immediately allowed to shorten, they performed a far greater amount of positive work when compared to being purely shortened alone (Cavagna et al., 1965; Cavagna et al., 1968). This sequential combination of eccentric (lengthening) and concentric (shortening) muscle actions was later termed the SSC (Cavanagh and Komi, 1979). In addition to when measured during isolated conditions, the apparent "performance enhancing" effect of the SSC was also demonstrated during a range of SSC actions involving the entire lower limb(s), such as running, jumping and hopping (Asmussen and Bonde-Petersen, 1974; Fukashiro and Komi, 1987; Luhtanen and Komi, 1978). Whilst it is important to note the SSC is common to upper limb movements too, such as throwing (Newton et al., 1997), the majority of scientific studies that have explored the SSC to date have solely investigated the lower limb(s) and so this chapter will discuss lower limb SSC actions only.

Due to its aforementioned prevalence in running, jumping and hopping movements, which are performed by many athletes as part of both training and competition, the SSC forms the most common type of lower limb muscle function (Van Ingen Schenau et al., 1997a). In recent years, there has been much debate over the proposed mechanisms which cause the potentiating effect (e.g., increased positive work) of the SSC, however, stimulation of muscle stretch reflexes (e.g., muscle spindles) and storage and reutilisation of elastic energy in the muscle-tendon unit (MTU) are the two primary mechanisms that have been repeatedly acknowledged among researchers (Cormie et al., 2011; Van Ingen Schenau et al., 1997a, 1997b; Turner and Jeffreys, 2011). During the SSC, stretch reflexes act to increase muscle stiffness (Taube et al., 2012), and tendon stiffness influences the storage and reutilisation of elastic energy (Farris et al., 2011), thus it can be deduced that MTS has a profound influence on SSC function.

WHAT IS STIFFNESS?

Simply stated, stiffness describes the relationship between a given force and the magnitude of deformation (i.e., stretch) of an object or body (Butler et al., 2003; Brughelli and Cronin, 2008a; McMahon et al., 2012). When applied to the MTU, the object or body could be the muscle, the tendon or

both. The term “stiffness” is based on Hooke’s Law, which has been described in detail elsewhere (Butler et al., 2003; Brughelli and Cronin, 2008a), and describes the stiffness of an ideal spring-mass system (Butler et al., 2003). When an object that obeys Hooke’s Law deforms (such as tendon), its change in length will be directly proportional to the force acting upon it (Alexander, 1997) (Figure 3.1). During this deformation (e.g., during the eccentric phase of a SSC action), the object will store elastic energy which will be reutilised as the object shortens (e.g., during the concentric phase of a SSC action) and returns to its original resting length (Butler et al., 2003). It is worth pointing out at this stage that activated muscle does not always adhere to Hooke’s Law and the reasons for this will be discussed in the later sections of this chapter. Nevertheless, during the performance of SSC actions, stiffness can be described at a broad range of levels, from an individual MTU, to modelling the entire body as a simple spring-mass system (Butler et al., 2003; Brughelli and Cronin, 2008a).

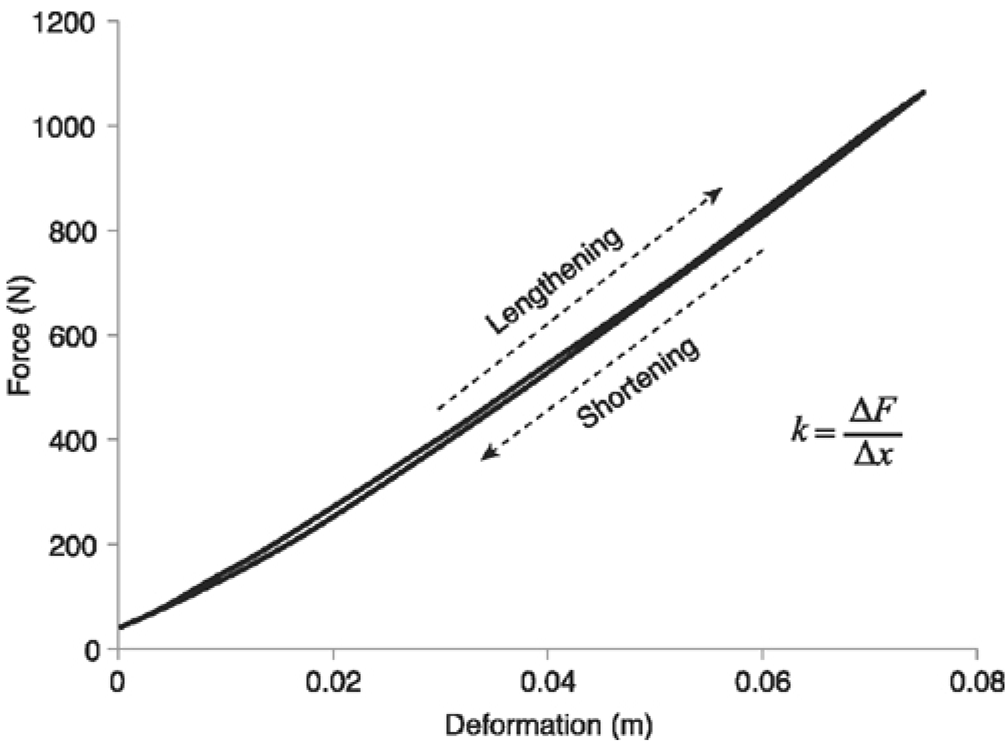

FIGURE 3.1 An example of an object that obeys Hooke’s Law and the equation to calculate stiffness (k), where ΔF = change in force and Δx = change in length.

MUSCLE-TENDON STIFFNESS

When considering stiffness in context of the various MTUs which surround the lower limb joints, it is known that there are both passive (tendon, connective tissue, etc., which are commonly referred to as the series and parallel elastic components) and active (muscle, which is commonly referred to as the contractile component) components. Due to this, the MTU is considered to be a variably stiff system because whilst tendon possesses a fairly linear relationship (due to it demonstrating mainly elastic behaviour) between force and deformation (Farris et al., 2011; Lichtwark and Wilson, 2005), muscle can vary its stiffness through both feedforward (e.g., pre-programmed) and feedback (e.g., reflex) activation mechanisms (Taube et al., 2012). It must also be noted that the tendon is known to possess viscous as well as elastic properties (Pearson and McMahon, 2012), and so the amount of tendon stretch (and thus storage of elastic energy) experienced during SSC actions will be somewhat affected by tendon loading rate (McMahon et al., 2014). Muscle activation is, therefore, the primary modulator of MTS during SSC actions, as this will influence both muscle stiffness (i.e., the resultant muscle length changes) and tendon stiffness (i.e., by affecting load rate) alike.

As mentioned earlier, both pre-programmed and reflex muscle activation strategies largely dictate the muscle stiffness attained during SSC tasks (Taube et al., 2012). The pre-programmed aspect of muscle activation relates to both muscle pre-activation, which acts to provide sufficient stiffness to the MTU at initial ground contact (Taube et al., 2012), and variable activation during ground contact, which helps to maintain stiffness (i.e., prevent muscle lengthening) in the braking phase and then facilitate the controlled release of high forces (produced in the braking phase) in the subsequent propulsion phase (Komi, 2003). The reflex aspect of muscle activation relates primarily to the stimulation of a stretch reflex called short-latency response (SLR), although when muscle is pre-activated prior to stretching (as is the case during SSC tasks) there are medium-latency (MLR) and long-latency (LLR) responses involved too (Taube et al., 2012). These reflex responses simply relate to their time-course of stimulation, with time epochs of 30–60 ms, 60–90 ms and 90–120 ms typically relating to the SLR, MLR and LLR, respectively. It has been suggested, however, that stretch reflex contributions to muscle stiffness are more apparent when the muscle is not fully activated (e.g., during sub-maximal SSC tasks

[Cronin et al., 2011]) in order to help prevent sudden muscle yielding during the braking phase (Taube et al., 2012).

Calculating individual MTS contributions to the total stiffness attained by a given MTU during SSC tasks is a relatively complex process which requires the simultaneous collection of ultrasound, electromyography, force platform and motion analysis data, followed by a lengthy data analysis process which makes this discrete level of analysis difficult to perform in a competitive sport setting. Thus, in the applied strength and conditioning research and practice setting, it is more common to see 'global' measures of lower limb MTS assessments, such as joint stiffness (K_{joint}) and leg stiffness (K_{leg}), as these measures are easier to attain, require less processing time and can still provide valuable insight into how MTS influences SSC function during a variety of athletic tasks (e.g., running, jumping, hopping).

JOINT STIFFNESS

Lower limb K_{joint} is typically calculated using the torsional-spring model (Figure 3.2) as the ratio of the peak sagittal plane joint moment (i.e., the joint rotatory force) to peak sagittal plane joint angular displacement (Figure 3.3) between the instants of ground contact and maximum joint flexion (Farley et al., 1998). An alternative method of quantifying K_{joint} has also been described in the literature as the ratio of negative mechanical work to change in joint angle between the instants of ground contact and maximum joint flexion (Arampatzis et al., 1999), however, this method was later critiqued (Gunther and Blickhan, 2002), and to the author's knowledge, has not since been reported in any other studies. Despite the method used, however, K_{joint} calculations require access to both a force platform and either two- or three-dimensional motion capture, so this equipment may be more accessible to strength and conditioning researchers and practitioners than the addition of ultrasound and electromyography equipment needed to calculate MTS. The torsional-spring model assumes that the lower limb can be represented by multiple spring-like joints (i.e., the ankle, knee and hip) during SSC actions, which flex and extend during the ground contact period, thus storing and releasing energy (Figure 3.2).

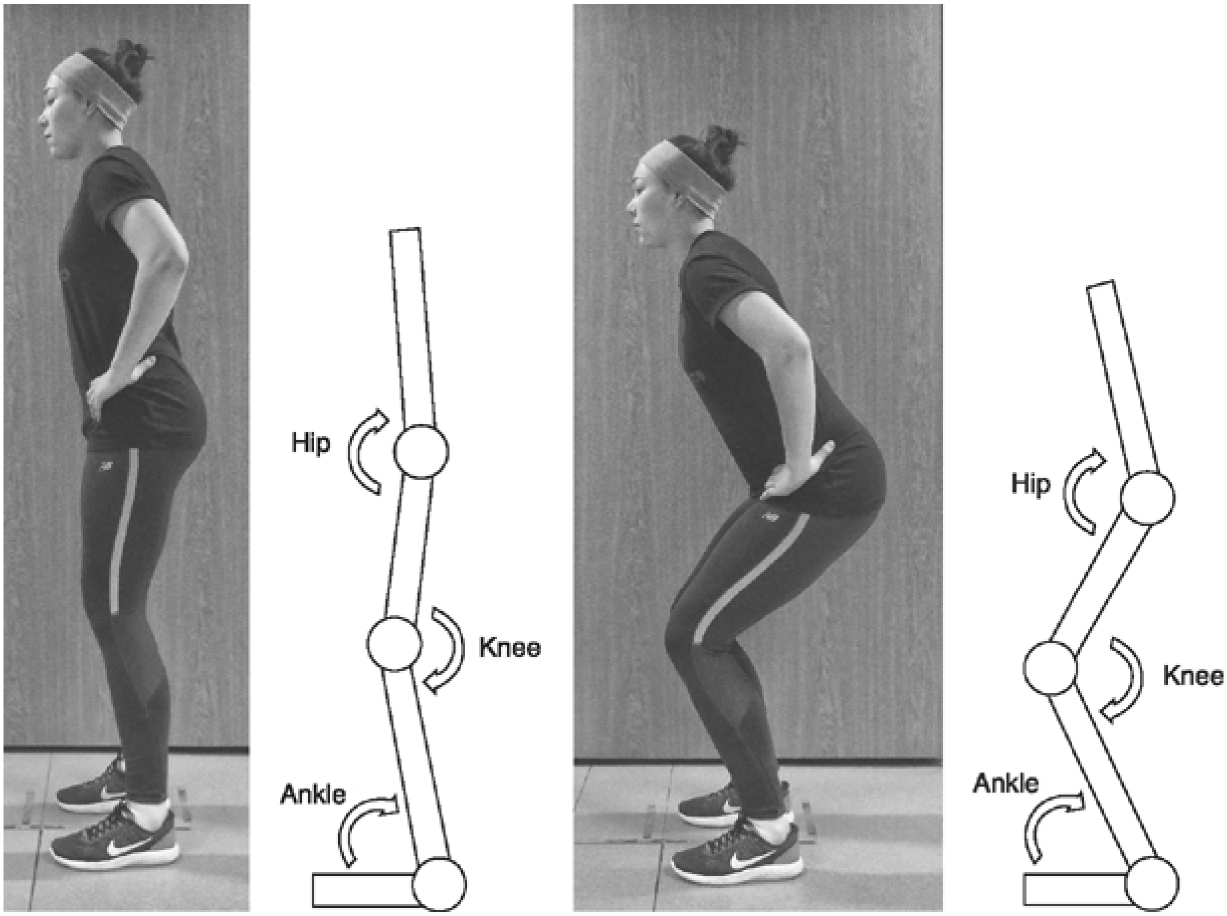

FIGURE 3.2 An example of the torsional spring model and how it corresponds to the human body.

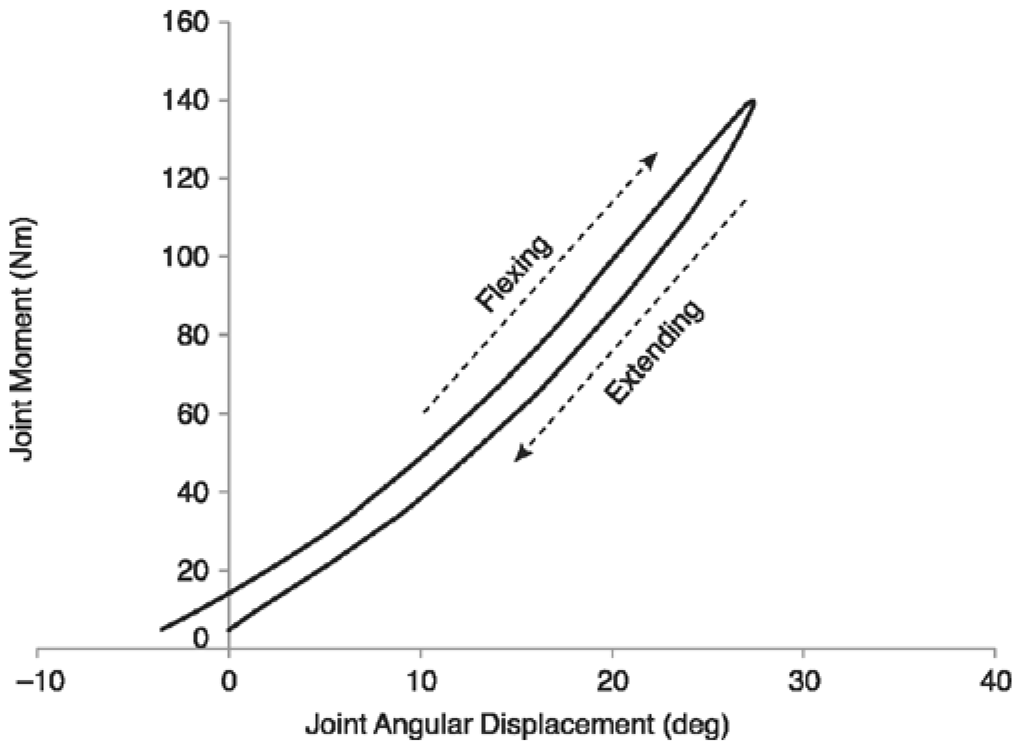

FIGURE 3.3 An example of the joint moment–joint angular displacement relationship during loaded flexion and extension.

It has been suggested that K_{joint} only provides a measure of 'quasi-stiffness', as one stiffness value is used to describe all contributing components to K_{joint}, such as muscles, tendons, ligaments, cartilage and bone (Latash and Zatsiorsky, 1993). Nevertheless, K_{joint} during SSC tasks is mainly influenced by the magnitude of agonist muscle activation, in addition to the magnitude of antagonist muscle co-activation, immediately prior to and during ground contact (Arampatzis et al., 2001b; Arampatzis et al., 2001a; Farley et al., 1998). Therefore, K_{joint} is mainly controlled by muscle stiffness through the muscle activation mechanisms mentioned in the previous section. Another point to consider is that K_{joint} attained during SSC tasks is also influenced by limb geometry at touchdown (Farley et al., 1998; Moritz and Farley, 2004; Devita and Skelly, 1992). This can be reasoned by the understanding of the joint moment–angle relationship, in that as the lower limb becomes more extended at touchdown, the moment about the joint decreases for any given external ground reaction force (Figure 3.4), resulting in decreased joint flexion for any given level of extensor muscle activation (Moritz and Farley, 2004).

LEG STIFFNESS

It has been shown in several studies that K_{joint} is the primary determinant of K_{leg} during SSC actions (Farley et al., 1998; Arampatzis et al., 1999; Kuitunen et al., 2002), and so although the predominant joint that regulates K_{leg} depends on the type of SSC task being performed, this most 'global' measure of lower limb stiffness provides valuable information pertaining to SSC function and is the easiest of the lower limb stiffness hierarchy to measure in both lab and field settings.

The K_{leg} measurement is based on the human body acting as a simple spring-mass system during SSC tasks (Brughelli and Cronin, 2008b; Geyer et al., 2006). The spring-mass model (Figure 3.5) is comprised of a point mass (equal to body mass), which is supported by a single massless Hookean spring (representing the leg or legs depending upon whether a unilateral or bilateral task is being performed) (Blickhan, 1989; McMahon and Cheng, 1990). When the spring is not compressed (i.e., during the flight phase of SSC tasks), it does not store any energy and thus no force is developed; however, energy is stored when the spring is compressed (i.e., during the braking phase of SSC tasks) and force is produced, and the majority of this energy is reutilised when the spring subsequently recoils (i.e., during the propulsion phase of SSC tasks) (Brughelli and Cronin, 2008a).

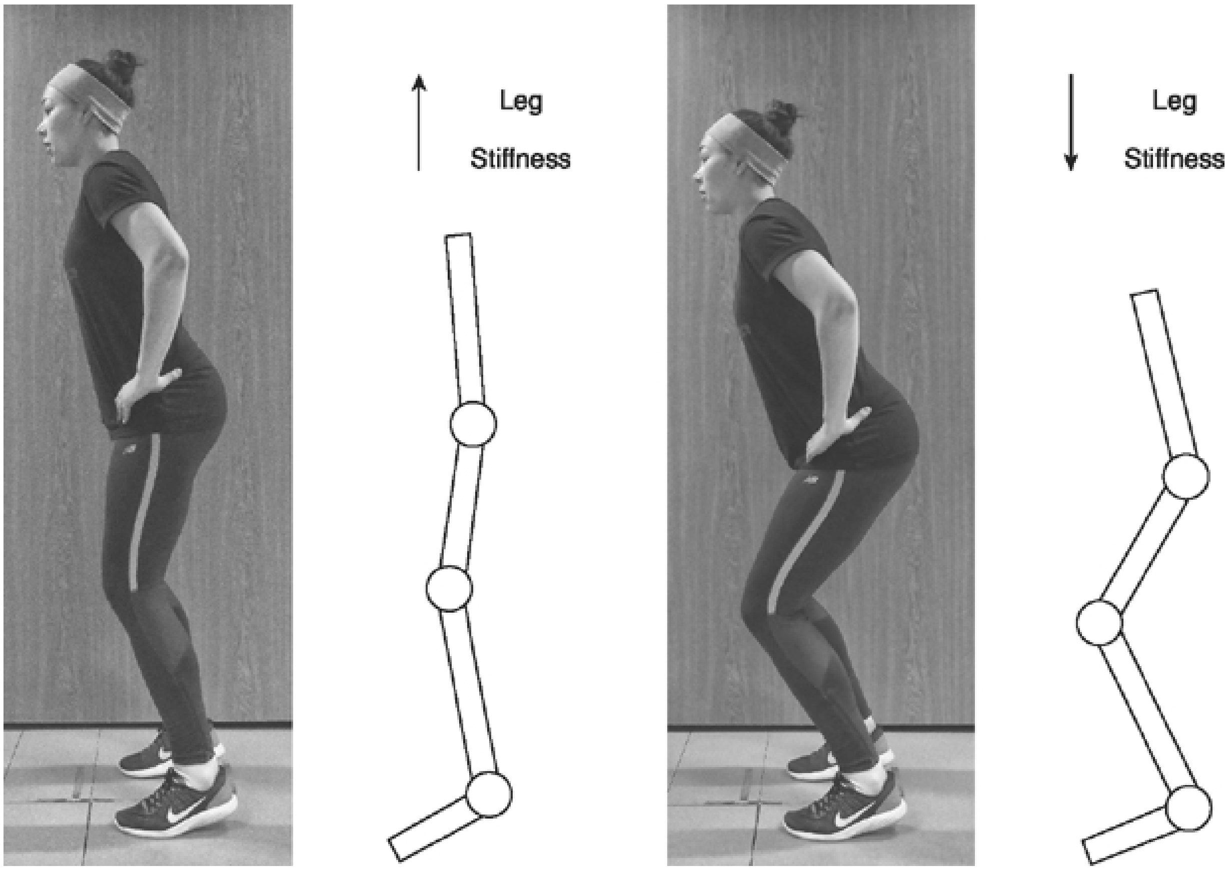

FIGURE 3.4 An example of how joint touchdown angles influence leg and joint stiffness values.

From the spring-mass model, K_{leg} can be calculated as the ratio of the peak ground reaction force to peak leg compression during the period of ground contact (McMahon and Cheng, 1990). Other methods can also be used to calculate K_{leg} based on body mass and either the natural period of oscillation (McMahon et al., 1987; Cavagna et al., 1988) or temporal characteristics such as ground contact and flight times (Morin et al., 2005; Dalleau et al., 2004). Although the latter methods (i.e., based on body mass and temporal factors) have been less frequently reported in the scientific literature (Brughelli and Cronin, 2008b; Serpell et al., 2012), they are commonly used in applied practice due to these measurements of K_{leg} being easily attainable from simple jump mats, photoelectric cells (e.g., Optojump) and even iPhone apps (Balsalobre-Fernández et al., 2017). The limitation of using field-based calculations of K_{leg} is that they do not directly include force and deformation in their calculations, and so they provide somewhat of a proxy of 'true' K_{leg}.

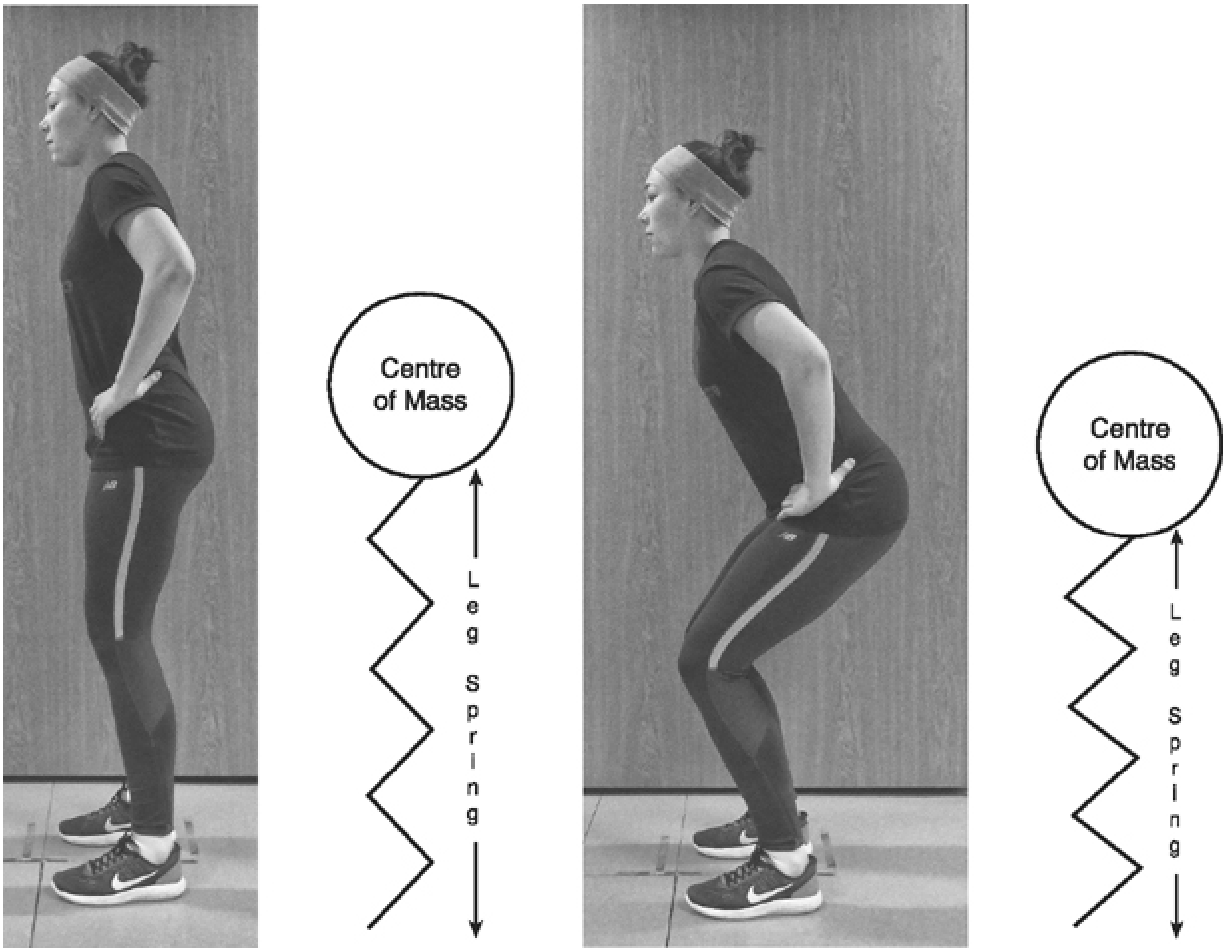

FIGURE 3.5 An example of the spring-mass model and how it corresponds to the human body.

STIFFNESS AND PERFORMANCE

The implications of MTS being primarily regulated by pre-programmed and reflex muscle activation, and somewhat influenced by tendon stiffness and joint geometry, is that it is acutely sensitive to changes in SSC task type and intensity which, in turn, influences SSC function (Ishikawa et al., 2005; Ishikawa and Komi, 2004; McMahon et al., 2014). For example, when bilateral drop jumps (DJs) were performed from increasing drop heights (10 cm lower than 'optimal' drop height, optimal drop height as determined by best jump height achieved, and 10 cm higher than 'optimal' drop height), vastus lateralis (VL) muscle activation increased, decreased and remained unchanged during the pre-contact, braking and propulsive phases, respectively, but tendon recoil decreased (Ishikawa et al., 2005). Tendon

recoil also reduced by virtue of increased drop height for the medial gastrocnemius (MG), and its activation patterns were similar to those reported for the VL in the pre-contact and braking phases; however, the MG showed increased activation during the propulsive phase (Ishikawa et al., 2005). Interestingly, the SLR amplitude decreased for the MG but increased for the VL during DJs performed from the highest drop (Ishikawa et al., 2005). This is perhaps explained by the MG showing a reduction in lengthening during the braking phase, whereas the VL demonstrated a general increase in lengthening during this phase (Ishikawa et al., 2005), since the muscle spindle stretch reflex detects the rate and magnitude of muscle lengthening (Taube et al., 2012). These results illustrate that variations in MTS and thus SSC function for a given task and intensity is muscle-specific (as noted by the differential response of the VL and MG MTUs), and that high stiffness (as shown for the highest drop condition) does not always transfer to improved performance (e.g., improved jump height).

The differential stiffness strategies of the individual VL and MG muscle-tendon components during various DJ tasks mentioned above (Ishikawa et al., 2005) are echoed by a range of studies that explored the associations between muscle activation strategies and both K_{leg} and K_{joint} attained in a range of DJ tasks. For example, there were significant correlations between K_{leg} and the magnitude of pre-activation of the MG, lateral gastrocnemius (LG), VL and the hamstrings during the performance of bilateral DJs by decathletes from a height of 20 cm (Arampatzis et al., 2001b). Interestingly, when DJs were performed from heights of 40 and 60 cm, relationships between K_{leg} and the magnitude of pre-activation were demonstrated for VL and the hamstrings only for this group of athletes (Arampatzis et al., 2001b). For female athletes, significant correlations between K_{leg} and the magnitude of pre-activation of the MG, LG and VL were found for bilateral DJs performed from a 20 cm height, whereas the magnitude of pre-activation of MG and VL only were correlated to K_{leg} attained during DJs from 40 cm (Arampatzis et al., 2001a). Nine healthy males also demonstrated a link between pre-activation of the VL muscle and K_{knee} during bilateral DJs performed from 50 cm (Horita et al., 2002).

The above results pertaining to the varying muscle activation responses to DJs performed from different drop heights reflect the different K_{joint}

contributions to total K_{leg} that have been highlighted for a range of performances. For example, K_{ankle} has been shown to be the primary determinant of K_{leg} during hopping in place at high (≥ 2.0 Hz) hopping frequencies whereby the ability to hop at high frequencies requires high levels of K_{leg} (Farley et al., 1998; Hobara et al., 2011). Contrastingly, K_{knee} was the primary modulator of K_{leg} at low (≤ 1.5 Hz) hopping frequencies which require lower levels of K_{leg} and where greater hop heights are noted (Hobara et al., 2011; Hobara et al., 2009). Similarly, K_{knee} was also the primary determinant of K_{leg} during both low (6.5 $m.s^{-1}$) velocity running (Arampatzis et al., 1999) and sprint running (Kuitunen et al., 2002). These differential joint contributions to total K_{leg} across different SSC tasks reflect differential muscle-tendon contributions to these tasks, with the contribution of tendon (in terms of total lengthening and shortening of the MTU) being higher and muscle length being almost constant (i.e., isometric) when K_{leg} increases (McMahon et al., 2013b).

Based on the results of the research presented above, it is apparent that there is an appropriate amount of K_{leg} for success in a particular SSC task. This notion is supported by a range of scientific studies related to jumping. For example, during DJ performances from heights of 20–60 cm, jump height was maximised when participants adopted a range of K_{leg} strategies (Arampatzis et al., 2001a, 2001b; Laffaye and Choukou, 2010). However, the general trend in these studies was that too much K_{leg} had a negative impact upon vertical jump height (Arampatzis et al., 2001a, 2001b; Laffaye and Choukou, 2010), and this was especially seen in a study whereby DJs were performed from very high (80 and 100 cm) drop heights (Walshe and Wilson, 1997). The potentially inhibiting effect of excessive K_{leg} was also demonstrated during a high jumping manoeuvre, as greatest jump heights were achieved when participants adopted a more compliant (i.e., less stiff) leg strategy (Laffaye et al., 2005). The aforementioned results suggest that the degree of K_{leg} required to successfully complete a jumping-based task depends upon both the aims (e.g., maximal height attainment vs. fast execution) and type (e.g., hopping vs. DJ) of the specific task being performed. Several studies have also reported that K_{leg} was associated with increased running velocity (Farley and Gonzalez, 1996; Stefanyshyn and

Nigg, 1998; Arampatzis et al., 1999; Hobara et al., 2010) and increased running economy (McMahon and Cheng, 1990, Heise and Martin, 1998, Dutto and Smith, 2002; Rabita et al., 2011) but not with sprint acceleration (Lockie et al., 2011; Chelly and Denis, 2001; Pruyn et al., 2014).

The reason for K_{leg} being beneficial to DJ from lower heights, as compared to DJ from greater heights and high jumping, can be explained by increased K_{leg} being linked to shorter ground contact times and increased vGRFs (ground reaction force) (Arampatzis et al., 2001a, 2001b). When increasing jump height is the desired outcome, vertical impulse (area underneath the force-time curve) must be increased (Kirby et al., 2011). Although impulse can be maintained or increased by increasing vGRFs when ground contact times decrease (as seen when employing a stiff jumping strategy), it seems the latter prevails when high K_{leg} is demonstrated in DJs performed from greater heights and during high jumping. Similarly, researchers have shown that the achievement of faster top running speeds was more closely related to the production of a greater resultant GRF rather than to an increase in stride frequency (Weyand et al., 2000). Therefore, if running was to be performed with high K_{leg}, ground contact times would decrease (Farley et al., 1991; Arampatzis et al., 2001b, 2001a), which would reduce the time available for force production (Weyand et al., 2010). A reduction in resultant GRF during running would likely reduce stride length (McMahon and Cheng, 1990; Kerdok et al., 2002). This is, like for jumping, due to a reduction in impulse. For example, unless a reduction in ground contact time is accompanied by at least the maintenance of, or an increase in, GRF, there will be a reduction in impulse. Therefore, top running speeds may plateau with an increase in K_{leg}, in spite of a potential increase in stride frequency (McMahon et al., 1987; Farley and Gonzalez, 1996; Hobara et al., 2010). Recent work did indeed find that the fastest man on earth (i.e., Usain Bolt) ran with significantly lower K_{leg}, lower stride frequency and longer ground contact times during competition when compared with his two closest rivals (Taylor and Beneke, 2012).

In terms of running economy, it is known that the storage and release of elastic energy will help to reduce the work of the muscle (Roberts and Marsh, 2003; Perl et al., 2012; Lichtwark and Barclay, 2010), and although previous studies revealed that a high K_{leg} strategy was associated with improved running economy (McMahon and Cheng, 1990; Heise and

Martin, 1998; Dutto and Smith, 2002; Rabita et al., 2011), a stiffer MTU may not always elicit a more economical outcome. For example, previous studies have examined the relationship between MG muscle fascicle length and Achilles tendon stiffness and maximum efficiency during a range of running and walking tasks (Lichtwark and Wilson, 2007, 2008; Lichtwark et al., 2007), and despite maximum efficiency for both running and walking occurring at similar values of tendon stiffness, it was suggested that moving towards a stiffer tendon would reduce efficiency in the walking task but would be more ideal for running, along with longer muscle fibre lengths required to optimise efficiency as compared to walking. However, modelling indicated that fibre lengths could vary by approximately one and a half times (45–70 mm) and tendon stiffness by approximately threefold (150–500 $N \cdot mm^{-1}$) to give optimal efficiency in a given walking or running task (Lichtwark and Wilson, 2008), which further highlights both the individual and task-specific nature of ‘optimal’ MTS.

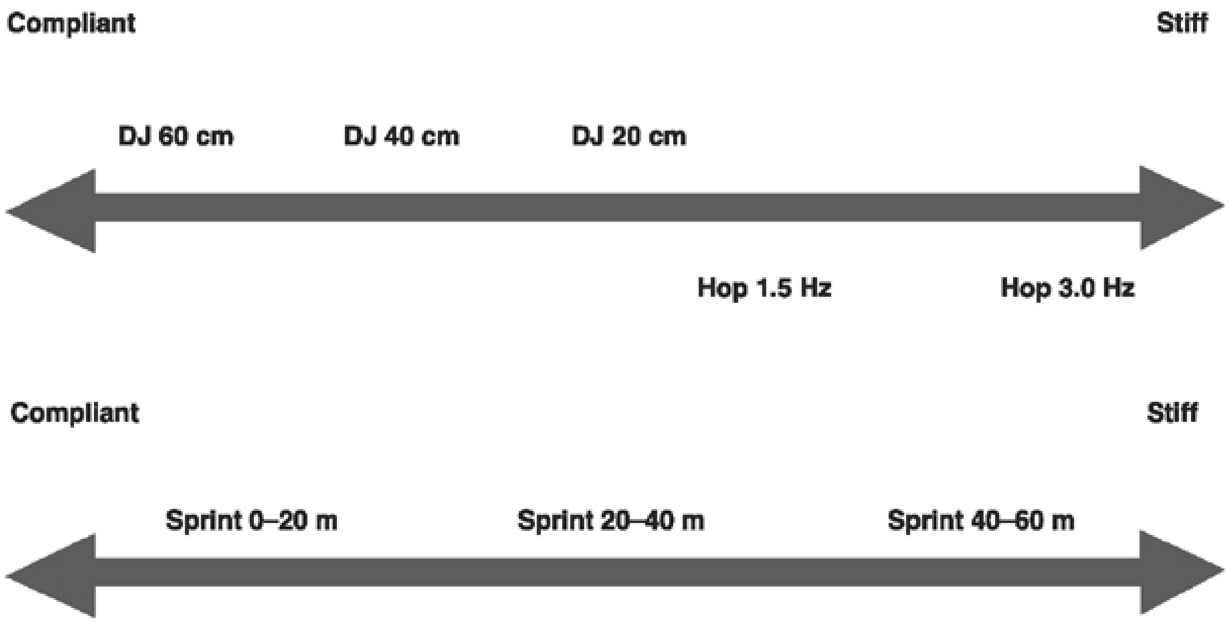

FIGURE 3.6 A schematic diagram illustrating how the leg(s) change from being more compliant (opposite of stiff) to more stiff for a range of stretch-shortening cycle tasks.

In conclusion, the amount of MTS required during a SSC task depends on desired task outcome (Figure 3.6). If reducing ground contact time and increasing GRF is sought then stiffer is better, but if increasing joint angular velocity to increase short sprint acceleration or jump height is sought then too much stiffness will be detrimental. Acutely modulating an athlete’s

MTS strategy in the direction of stiffening their legs via verbal coaching cues, etc., will increase GRFs and load rates, and so this should only be done if they are appropriately conditioned and (in line with the previous point) if the task warrants a stiffer strategy (Figure 3.6). A safer and more sensible approach to increasing MTS is through long-term training.

STIFFNESS AND TRAINING

Only a few studies to date have examined the effects of training interventions on K_{leg} and K_{joint}, as determined during SSC actions (Table 3.1). Most of the training interventions included in these studies were very distinct, which makes it somewhat difficult to make any definitive conclusions about the most effective training methods for increasing K_{leg} and K_{joint}, but there are some general trends noted across studies which warrant discussion.

Generally, traditional resistance exercises performed individually with ≤80% one repetition maximum (1RM) tended not to increase K_{leg} and K_{joint} (Toumi et al., 2004; Kubo et al., 2007), unless performed concurrently with plyometric exercises (Toumi et al., 2004). Individual traditional resistance exercises can increase K_{leg}, however, if performed with a relative load of up to 90% 1RM (Cormie et al., 2010). Multiple traditional resistance exercises performed with ≥85% 1RM have been shown to increase task-specific K_{leg} (Millet et al., 2002; Arabatzi and Kellis, 2012). For example, the results presented by Millet et al. (2002) showed increased K_{leg} measured during running but not during hopping at 2.0 Hz. These task-specific differences in K_{leg} seen post-intervention are most likely due to the training programme being knee-dominant (Table 3.1), in light of K_{knee} being the primary modulator of K_{leg} during running (Arampatzis et al., 1999; Kuitunen et al., 2002) and K_{ankle} being the primary determinant of K_{leg} when hopping at 2.0 Hz (Farley et al., 1998; Hobara et al., 2011). Contrastingly, the training programme included in the study by Arabatzi & Kellis (2012) was also knee-focussed, although K_{leg} increased during DJs performed from 20 cm but not 60 cm, despite the latter drop height being more synonymous with K_{knee} regulation (Arampatzis et al., 2001b); this is possibly due to the

relatively short training duration of 8 weeks. Similarly, moderate-heavy (60–100% 1RM) traditional resistance exercise performed concomitantly with plyometric exercises increased K_{leg} during countermovement jump performance, but reduced K_{leg} during DJs performed from ≥30 cm drop heights (Hunter and Marshall, 2002). However, the participants tested by Marshall and Hunter (2002) had never performed any structured plyometric training prior to the commencement of the study nor were they given any verbal instructions either prior to or during the jump performances, which may have influenced these findings.

TABLE 3.1 A summary of studies which have determined the effects of training interventions on global lower limb stiffness measures

Study	*Subjects*	*Training Programme Overview*	*Training Duration*	*Result*
Toumi et al. (2004)	8 male handball players	6 × 10 reps of leg press at 70% 1-RM	6 weeks (4 sessions/week)	No change in K_{leg} (CMJ)
Cormie et al. (2010)	8 strength trained males	7 × 6 reps of jump squat at 0% 1-RM (2 sessions) & 3 × 5 reps of jump squat at 30% 1-RM (1 session)	10 weeks (3 sessions/week)	Increase in K_{leg} (CMJ)
Connie et al. (2010)	8 strength trained males	3 × 3–6 reps of back squat at 75–90% 1-RM	10 weeks (3 sessions/week)	Increase in K_{leg} (CMJ)
Hunter & Marshall (2002)	14 males (mixed sports)	1–4 × 3–8 reps of CMJs, 1–2 × 6–10 reps of DTs (30–90cm) & 2–3 × 6–10 reps of deadlift/squat at 60–100% 1-RM	10 weeks (2 sessions/week)	Increase in K_{leg} (CMJ) Decrease in K_{leg} (DJ 30,60 & 90 cm)
Millet et al. (2002)	7 male triathletes	3–5 × 3–5 reps of hamstring curl, leg press, seated press, parallel squat, leg extension, & heel raise at >90% 1-RM	14 weeks (2 sessions/week)	No change in K_{leg} (hopping) Increase in K_{leg} (running)
Arabatzi & Kellis (2012)	9 physically active males	4–6 × 4–6 reps of power clean, snatch, clean and jerk, high pull, half-squat at >85% 1-RM	8 weeks (3 sessions/week)	Increase in K_{leg} (DJ 20 & 60 cm)
Arabatzi & Kellis (2012)	9 physically active males	4–6 × 4–6 reps of leg press, leg curl, leg extension, bench press, half-squat at >85% 1-RM	8 weeks (3 sessions/week)	Increase in K_{leg} (DJ 20 cm) Decrease in K_{leg} (DJ 60 cm)
Toumi et	8 male	6 × 10 reps of leg press at 70% 1-	6 weeks (4	

al. (2004)	handball players	RM & 3 × 5 reps of cross-over jump	sessions/week)	Increase in K_{leg} (CMJ)
Kubo et al. (2007)	24 physically males	5 × 10 reps of unilateral hopping & DJs (20cm) at 40% 1-RM	12 weeks (4 sessions/week)	Increase in K_{ankle} (DJ 20 cm)
Kubo et al. (2007)	24 physically males	5 × 10 reps of unilateral calf raise at 80% 1-RM	12 weeks (4 sessions/week)	No change in K_{ankle} (DJ 20 cm)

Notes: CMJ = countermovement jump, DJ = drop jump

In contrast to the contradictory K_{leg} and K_{joint} adaptations brought about via traditional resistance training interventions mentioned above, all training programmes that included either plyometric, ballistic or Olympic weightlifting exercises increased K_{leg} and K_{joint} (Cormie et al., 2010; Kubo et al., 2007; Arabatzi and Kellis, 2012). The differential adaptations to K_{leg} and K_{joint} following different exercise modalities and intensities have been attributed to the different mechanisms that modulate MTS attainment. For example, heavy resistance training (≥80% 1RM) leads to greater strength (i.e., muscle force) capacity, and although muscle strength is not a direct measure of muscle stiffness, it can be thought of as a proxy for stiffness (Pearson and McMahon, 2012). Additionally, tendon stiffness, is related to the force producing capacity of the muscle (Arampatzis et al., 2007; Muraoka et al., 2005), and, as has been shown in several studies, tendon stiffness increases in response to traditional resistance training, in addition to isometric and eccentric-focussed training (refer to the recent systematic review and meta-analysis on this topic by Bohm et al., 2015). Alternatively, enhanced muscle recruitment strategies (as is commonly associated with plyometric training and weightlifting [Chimera et al., 2004; Arabatzi and Kellis, 2012]) may explain increased post-training K_{leg} and K_{joint} (Taube et al., 2012), as muscle strength and tendon stiffness generally do not increase following plyometric training (Kubo et al., 2007; Bohm et al., 2015) unless performed with a very high volume (Fouré et al., 2010, 2011).

The mixed results of training studies presented in Table 3.1, particularly when interpreted alongside the underpinning mechanisms for MTS adaptation, highlight the efficacy of including both traditional resistance (i.e., strength) and power-focussed exercises in a training programme

designed to increase MTS. Traditional resistance exercises, particularly when utilised by relatively weak athletes, should be performed for at least 8–12 weeks as this is the minimum amount of time likely needed to induce increases in tendon stiffness, despite muscle strength gains occurring from as soon as 4 weeks (Kubo et al., 2012, 2010). If an athlete is relatively strong then it may be prudent to include low-load SSC tasks alongside traditional resistance exercises (particularly as they progress through the training weeks) to facilitate the previously mentioned enhanced muscle activation strategies that can be gained through this (Chimera et al., 2004). Because increases in muscle strength generally outweigh increases in tendon stiffness, due to the differential time-course of adaptation of these structures to resistance training (Kubo et al., 2012, 2010), moderate-high-load SSC tasks performed too early may lead to excessive strain of the lower limb tendons (McMahon et al., 2013a). Thus these should be avoided until at least after the 12-week resistance training period, unless the athlete is deemed to be 'strong' (see Chapter 2) and is used to performing such SSC tasks.

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CHAPTER 4

Endocrinology and resistance training

Anthony Turner and Christian Cook

INTRODUCTION

The endocrine system includes all tissues and glands that secrete hormones into the circulatory system. In this chapter, we focus on those involved in resistance training, mainly (1) the anabolic hormone (those that directly or pervasively promote tissue building) testosterone and (2) the primary catabolic hormone (promoting tissue degradation or repartitioning of energy reserves) cortisol. To a large extent, these hormones can influence our motivation to train, the loads we lift, performance gains and our ability to cope with large volumes of training stress. Naturally then, understanding their effects as part of a periodised strength and conditioning (S&C) programme is important if increases in strength, hypertrophy and general performance are to be optimised; providing this information is therefore the aim of this chapter.

Testosterone (T) and cortisol are affected by the following strength training variables: exercise modality (involved musculature), exercise sequence, intensity (load), sets and repetitions (volume) and rest period. They are also affected by preconditioning (priming) strategies (discussed in Chapter 10) and environmental stimuli, such as observers, training partners and visual images, for example. Finally, the individual athlete is also a factor, with elite athletes often showing different patterns to sub-elite counterparts due to training history and base line strength. The

manipulation of each of these variables will be discussed throughout, but first we will describe the fundamental role of receptors and the significance of muscle remodelling.

HORMONE-RECEPTOR COMPLEX

Hormones can be defined as chemical messengers that are transported to specific target cells which possess specific hormone receptors. The specificity of a hormone and its receptor is often explained using the lock and key theory, whereby the receptor is the lock and the hormone is the key. It is important to note that while the concentration of hormones is important, so too is the number of receptors available, as this ultimately determines the possibility of interactions. For example, when a cell has reached its genetic ceiling for adaptation (e.g., through protein accretion), receptors may become non-responsive and down-regulate, thus reducing the probability of hormonal binding (Kraemer et al., 2008). Alternatively, receptors can up-regulate and increase the probability of interactions. In essence, exposure to T and stress can alter both affinity and the number of androgen receptors, which can change the probability of a response (Basualto-Alarcón et al., 2013). For example, Kadi et al. (2000) reported that in response to continued resistance training, power lifters had a greater number of androgen receptors in their trapezius muscle, and thus an enhanced ability to use T. In addition, Ratamess et al. (2005) have shown significant correlations between baseline androgen receptor content in the vastus lateralis and 1RM squat, further suggesting that androgen receptor content may assist in mediating strength changes during resistance training.

MUSCLE REMODELLING

Muscle remodelling involves the disruption of muscle fibres (stimulus/load dependent) in response to mechanical loading, resulting in the inflammatory process (immune cells and catabolic hormones) and subsequent release of anabolic hormones (Clarkson & Tremblay, 1998). In addition, mechanical loading increases receptor and membrane permeability to hormones and nutrients, therefore tissue activation may be considered a precursor to anabolism (Kraemer & Ratamess, 2005). Consequently, only the recruited

muscle fibres can be remodelled (Kraemer et al., 2008), emphasising the need to exercise muscle groups in a sport-specific manner (including range of motion, muscle action, velocity of movement, force generation and relative intensity), and the need to utilise progressive overload. The latter will increase motor unit recruitment, thereby exposing a greater number of muscle fibres to hormone-tissue interactions (Kraemer & Ratamess, 2005).

Given the need to induce muscle damage (and thus an inflammatory response) so that adaptations can occur, it is interesting to consider whether implementing recovery strategies during phases in which hypertrophy is the goal, is actually detrimental. Because hypertrophy occurs in response to damage, strategies that actually reduce the subsequent inflammatory response, such as contrast water therapy, compression garments and massage, may limit its effect. Such suggestions may influence team-sport, pre-season recovery routines, where hypertrophy may be sought, vs. in-season routines, where performance maintenance is fundamental and must be quickly re-established following games. Current practices thus appear to discourage recovery strategies in the off-season, and only include them during the season and when in close proximity to competitions. This theory is discussed further in Chapter 12.

TESTOSTERONE

Testosterone is responsible for the development of male secondary sex characteristics, spermatogenesis and the male skeletal system. Pertinent to this discussion, T is involved in the muscle growth and protein retention observed during strength training through its direct (i.e., muscle growth) and indirect (e.g., stimulation of growth hormone and neuron receptors and effects on training motivation) affects on muscle tissue (Fleck & Kraemer, 2004; Kraemer et al., 2008). Moreover, due to its anabolic effects, the levels of circulating T have been proposed as a physiological marker to evaluate the anabolic status of the body (Hakkinen et al., 1985). Finally, T is also related to behaviour modification, and more recent research appears to see this as being its greatest asset within training and performance adaptations; our discussion of T thus starts here.

Testosterone and behaviour

Testosterone's correlation to strength and hypertrophy may reflect its biomarker potential for stress, rather than simply its direct anabolic effects on muscle (Crewther et al., 2012). More recent research in sport has started to exploit T's known effect on behaviour (Aleman et al., 2004), including increasing aggression (Hermans et al., 2008), risk-taking (Ronay & von Hippel, 2010) and unconscious motivation (Aarts & van Honk, 2009), as well as exploring its modulation via non-physical interventions. This has been demonstrated previously, for example, through visual images including sports fans watching their teams win (Bernhardt et al., 1998), competing at the home stadium (Neave & Wolfson, 2003) and watching previous victories (Carré & Putman, 2010). Also through watching a sexually arousing film (Stoléru & Ennaji, 1993) and being in a position regarded as powerful in display (Carney & Cuddy, 2010). Therefore, it has been proposed that utilising T's ability to modulate behaviour through increased training motivation will positively influence training based outcomes (Cook & Beaven, 2013). In fact, in elite athletes who train closer to their maximum, this effect may be more influential than that of anabolism; these qualities result in a higher quality and quantity of work performed which in turn promote strength and hypertrophy using other anabolic functions. Given these findings, the S&C coach can maximise sessions and competition performance by identifying methods of psychological priming or preconditioning.

In support of such priming, the volitional training performance of elite female athletes when self-selecting a 3RM workload was strongly related to individual variation in pre-exercise salivary T concentrations within a training program. Relationships were found in the bench press (R_2 = 0.70), back squat (R_2 = 0.45) and power production via a maximal-distance medicine ball throw (R_2 = 0.50); similar results have also been found in males (Crewther et al., 2009a). Therefore, volitional workload selection and performance are correlated to relative pre-exercise salivary T levels. As such, in elite athletes, free T may be a useful marker of voluntary effort and its role here may supersede its role on muscle hypertrophy via protein synthesis. For example, given that small, between-session increases in total load (i.e., continued overload) are indicative of adaptations and become more difficult as the athlete progresses in training age, the athlete's voluntary effort partially reflects their state of motivation, recovery and readiness to perform in individual training sessions (Cook & Beaven,

2013). Interestingly, then, previous associations found between strength, power and T levels (discussed below) may also be related to an enhanced psychological desire to perform well. Therefore, in addition to priming T via physical interventions such as prior workouts and exercise order (again discussed below), T may also be primed via non-physical interventions such as videos, feedback and peer assessment; a summary of studies examining this is outlined in Table 1.

Testosterone and strength and power

As well as cellular interactions, T can bind with receptors on neurons and therefore increase instantaneous muscle strength and recruited muscle mass (Kraemer et al., 2008; Kraemer & Ratamess, 2005). This is achieved through an increase in neurotransmitter release and structural adaptations of the neuromuscular junction (Fleck & Kraemer, 2004; Nagaya & Herrera, 1995), where T-nervous interactions can regenerate nerves and increase the cell body size and dendrite length and diameter (Nagaya & Herrera, 1995). These neural adaptations (along with behavioural modifications), coupled with its effects on calcium handling and muscle contractility (Curl et al., 1989), may demonstrate an advanced strategy to increase force capability. For example, basal serum T levels have been correlated to average power output, jump height and both power and work performed during 60s continuous jumping (Bosco et al., 1996b). Basal T levels have also been correlated with countermovement jump height, strength and sprint speed in professional male rugby players (Crewther et al., 2012; Crewther et al., 2009b), soccer players (Bosco et al., 1996a) and elite women athletes (Cardinale & Stone, 2006). These correlations may be due, in part, to T's significant effects on motor neurons (Viru et al., 2003), and serves to highlight the importance of increased T concentrations and the significance of T-nervous interactions within sports performance. Given the aforementioned benefits of T on strength, power and training motivation, it appears prudent to coincide training with periods of increased T availability.

TABLE 4.1 Individual studies examining the priming of testosterone via non-physical interventions such as videos, feedback and peer assessment

Motivational videos
Cook & Crewther (2012a) examined the acute effects of video clips on salivary T and cortisol (C)

concentrations and subsequent 3RM squat performances in elite male rugby players. They found that significant ($p > 0.001$) increases in T concentrations were noted with watching erotic, humorous, aggressive and training videos, with T decreasing significantly (versus control) after a sad clip. A significant improvement in 3RM performances was noted after the erotic, aggressive and training clips and a strong within-individual correlation ($r = 0.85$) was noted between the relative changes in T and the 3RM squats across all video sessions. Finally, the aggressive video clip induced the largest relative change in T. The authors suggested that findings may be related to T's (behavioural) effect on risk-taking (Ronay & von Hippel, 2010), whereby they were willing to try and lift a heavier weight.

Pre-match video with feedback

Given that a pre-match talk, often with video analysis, is commonplace in elite sport, Crewther & Cook (2012b) assessed the T and C response following this. They hypothesised that watching a video clip of successful skill execution by the player with positive coach feedback (VPCF) would produce the largest pre-game T responses, the smallest cortisol (C) responses and the best performance outcomes. This was compared to watching a video clip of successful skill execution by an opposing player with cautionary coach feedback (VCCF), and the player left alone to self-motivate (SM). Salivary free T and C, along with player performance as rated by the coach, were indeed best in the former condition, with VCCF producing the largest C response. Across all treatments, greater individual T responses and lower C responses were associated with better performance outcomes.

Post-match video with feedback

Crewther and Cook (2012) tested the effects of different post-match video and feedback interventions on the subsequent hormonal responses to a physical stress-test (i.e., three sets of power cleans, back squats and bench press) and game performance in professional rugby union players. On four occasions, players completed a video session (one hour each) with accompanying coach feedback the day after a rugby union match. The interventions showed either video footage of player mistakes with negative coach feedback (NCF1) or player successes with positive feedback (PCF1). The PFC approach was associated with significantly ($p > 0.01$) greater free T (36% to 42%) and associated with higher (28% to 51%) pre-game T concentrations and superior game-ranked performances. The authors concluded that the post-game presentation of specific video footage combined with different coach feedback influenced the free hormonal state of rugby players and game performance several days later. Their results further support the reciprocal model (Mazur & Booth, 1998), which states that free hormones not only influence behaviour, but also are in turn affected by behaviour.

Social environment and video presentations

Cook & Crewther (2014) examined the social environment effects during a post-match video presentation on the subsequent hormonal responses and match performance in professional male athletes. To modify the social environment the video presentations were completed in the presence of: (1) strangers who were bigger (SB), (2) strangers who were smaller (SS), (3) friends who were bigger (FB) and (4) friends who were smaller (FS). The T responses to the stress test differed in magnitude across each intervention (SS > SB and FB > FS), as did C responsiveness (SB > SS > FS and FB). This agreed with previous research showing that T levels increased when they defeated strangers, but not their friends (Wagner et al., 2002). Differences in male T concentrations have also been demonstrated when interacting socially with other males simply perceived to be similar (i.e., increasing T) or dissimilar (i.e., lowering T) (DeSoto et al., 2009). Coaches can use this information to determine the suitability of feedback, not simply in terms of whether it is positive or not, but the audience with which it is shared in front of.

Manipulating exercise sessions to enhance testosterone release

Testosterone exhibits diurnal variations whereby concentrations are typically higher in the morning and drop throughout the day; this is also the case for cortisol, however (Lejune-Lenain et al., 1987). The question emerges of whether it is better to exercise in the morning when concentrations are highest, or to exercise in the evening to maintain increased concentrations throughout the day (Kraemer et al., 2008). Cook et al. (2013) have investigated the effect of offsetting the circadian decline in T through morning training; they compared the efficacy of a morning strength or sprint session on afternoon performance. They found that the addition of morning short sprints potentiated subsequent afternoon sprints only, however, a short weights session increased not only afternoon sprint performance, but also measures of maximal strength and lower body power; both interventions increased T above a control group. This finding is supported through data investigating afternoon throwing performance in shot-putters following a morning resistance training session (Ekstrand et al. 2013). Here afternoon throwing performance was improved for up to 6 hours.

Teo et al. (2011) investigated the effects of circadian rhythm on a single training session on maximal force production and power output. Results revealed that both, measured within countermovement jumps, squat jumps, isometric pulls and 1RM squats, were highest at 4 p.m. compared to 8 a.m. (lowest), 12 p.m. and 8 p.m. (both similar). This pattern was mirrored by aural temperature, with the increase in body temperature considered largely responsible. Four p.m. also revealed the lowest rating of perceived exertion (RPE) and collectively data argues that coaches and athletes should consider scheduling training or testing sessions around this time (Teo et al., 2011), or at least consider the significance an increase in core body temperature has; this is discussed further in Chapter 10. Perhaps two sessions, with the first being resistance training based and the second, consisting of more sport-specific speed and power based drills, commencing at 4 p.m., is ideal.

Beaven et al. (2011) investigated the ordering of exercises within a training session to identify which exercise sequence provides an enhanced

anabolic milieu for adaptation; specifically, should you programme strength exercises first or power exercises first? The power block consisted of three sets of three repetitions of jump squat exercise at 50% of 1RM and the strength block consisted of three sets of three repetitions of box squat at 3RM. The hormonal response after the strength–power bout was greatest, demonstrating small increase in T (13% ± 7%) and a trivial increase in cortisol (27% ± 30%). Results thus suggest that this exercise sequence is optimal in creating an anabolic environment.

Finally, T concentrations during training sessions have been reported to remain elevated for up to 45 to 60 minutes and decrease from then on (Zatsiorsky & Kraemer, 2006). Viru et al. (2003) further suggested that following training sessions of 1-hour duration, the testosterone: cortisol (T:C) ratio (discussed below) may decrease as a fatigue phenomenon. It may be prudent therefore to limit exercise sessions to ≤60 minutes as beyond this duration the session may begin to progress towards catabolism, whereby more receptors become responsive to cortisol interactions. Such an approach possibly warrants splitting the days training objectives into two to three ~30 minute sessions, rather than one longer duration session. However, it should be noted that such advice may best suit strength and power based training as hypertrophy sessions may be required to extend beyond this given the need to train to failure across multiple exercises; more recent research defines this as more important than the concentration of hormones. This is discussed below.

Manipulating acute resistance training variables to enhance testosterone release

Large muscle group exercises such as squats, deadlifts (Fahey et al., 1976), Olympic lifts (Kraemer et al., 1992) and jump squats (Volek et al., 1997) significantly increase T concentrations, whereas little or no change has been reported with bench press and exercises involving smaller musculature (Kraemer et al., 2008; Fleck & Kraemer, 2004). It may be advised that, within a training session, large muscle group exercises are performed before small muscle group exercises in order to expose the smaller musculature to the increased concentrations of T (Kraemer & Ratamess, 2005). This is supported by Hansen et al. (2001) who measured strength changes in elbow flexors following nine weeks of strength training. Two groups performed

elbow flexion exercises, however, one group preceded these with lower body exercise. Only this group significantly increased acute T concentrations with concomitant increases in the strength of the elbow flexors.

Hakkinen & Pakarinen (1993) report increases in T (and growth hormone) following ten sets of ten repetitions at 70% 1RM, but no significant changes following twenty sets of 1RM. Further, Bosco et al. (2000) reported no change following ten sets of two to three repetitions, but when the volume increased to twenty sets of two to four repetitions, increases in T were noted. A moderate to high volume of exercise, achieved with multiple sets, repetitions or exercises may be required as the release of T may be correlated with lactate accumulation (Lin et al., 2001; Linnamo et al., 2005; Lu et al., 1997). Kraemer et al. (1991, 1990) and Beaven et al. (2008a) summarise that bodybuilding (hypertrophy) programmes, utilising moderate load, high volume training, with short rest periods are most effective for stimulating acute T increases.

It should be noted that this prescription of training (three sets of ten repetitions, short rest periods) also notes the highest release of growth hormone with both hormones seemingly released maximally following high levels of lactate and hydrogen ions (Godfrey et al., 2009). It may be that lactate acts as a pseudo-hormone, but further research is required to fully elucidate its signalling role in this context (Godfrey et al., 2009). This association explains the muscle group-focussed sessions and short rest periods of bodybuilders, as sessions that alternate between body parts may allow for the dissipation of lactate and therefore reduce the T and growth hormone (GH) response. It may also explain the commonly used slow-continuous method (e.g., 4s concentric and 4s eccentric), as this would increase time under tension (facilitating the accumulation of lactate and hydrogen ions (H^+), reduce local blood circulation (with total occlusion occurring at loads >45% 1RM) and promote venous pooling. The consequent promotion of blood pooling and fluid volume shifts in order to maintain osmotic pressure may then increase the concentration of hormones, time available for interaction and, therefore, the probability of hormone-receptor interactions. It must be noted, however, that such low velocity training does not translate effectively to enhanced strength, power or performance in athletic tasks.

Testosterone, growth hormone and hypertrophy

Despite the above research, sole reliance (or rather assumed best practice) on the above "body-building" style programming to design hypertrophy-based sessions has become contentious. Recent studies have questioned the direct role of T and growth hormone in response to exercise stimuli in promoting hypertrophy and indeed strength; these suggest that neither circulating hormones nor indeed load (Morton et al., 2016; Schoenfeld et al., 2015; West et al., 2009; West & Phillips, 2012) affect these outcomes. While they, like others, have shown that concentrations of T and growth hormone (and also cortisol) are increased as a result of an acute exercise bout ($p < 0.001$) over a 12-week training period (training 4 times/week), there is no significant change from baseline, and nor do concentration changes significantly correlate with any physical measure (e.g., changes in muscle cross sectional area, lean body mass and strength increases in the bench, shoulder and leg press). Instead, both hypertrophy and strength increases can be achieved through high and low repetition training (using loads of 30–50% and 75–90% of 1RM, respectively) provided exercises are performed until volitional failure (Morton et al., 2016). The comparable gains in muscle cross sectional area and strength of high repetition training (relative to low repetition training) are likely because the former involves a higher volume, which requires maximal activation of motor units (Morton et al., 2016). It should be noted, however, that strength gains are still greatest using higher loads; this is discussed briefly below, but more detail is found in Chapter 2.

There is growing consensus that volume load and training to muscular failure are the causative factors for muscle hypertrophy. The latter increases motor unit recruitment and thus the quantity of muscle fibres that are exposed to the stimulus and undergo the remodelling process. Perhaps traditional hypertrophy programmes (i.e., three sets of ten, short rest) are only more beneficial with respect to time, as you can fit more volume in within a shorter period of time? These answers may be further gleaned from the studies identified in Table 4.2.

TABLE 4.2 Individual studies examining load, rest and hormones on hypertrophy and strength
Effects of low vs. high load resistance training on muscle strength and hypertrophy
Schoenfeld et al. (2015) compared a low load routine of 25–35 repetitions to a moderate load

routine of 8–12 repetitions. Both groups performed three sets of seven different exercises representing all major muscles, with all sets performed to or near failure. Training was performed three times per week on non-consecutive days, for a total of eight weeks. Both high load and moderate load conditions produced significant increases in cross-sectional area (CSA), with no significant differences between groups. Improvements in back squat and bench press strength were greatest in the high load group, but only significant in the former. Upper body muscle endurance (assessed by the bench press at 50% 1RM to failure) improved, albeit non-significantly, to a greater extent in low load group. Both load conditions can increase hypertrophy, with changes in strength and endurance showing some specificity to load.

Effects of different volume-equated resistance training loading strategies on muscular adaptations

Schoenfeld et al. (2014) investigated adaptations to a volume-equated bodybuilding-type training program (3 sets of 10 with 90s rest) vs. a powerlifting-type routine (7 sets or 3RM with 3min rest) in well-trained subjects. After eight weeks, no significant differences were noted in muscle thickness of the biceps brachii, but significant differences were found in 1RM bench press, and a trend was found for greater increases in the 1RM squat; these gains naturally favoured the powerlifting approach. In conclusion, this study showed that both bodybuilding- and powerlifting-type training promote similar increases in muscular size, but powerlifting-type training is superior for enhancing maximal strength.

The effect of inter-set rest intervals on resistance exercise-induced muscle hypertrophy

Henselmans & Schoenfeld (2014) investigated the effect of inter-set rest intervals on resistance training-induced muscular hypertrophy. Their review revealed that the rest period recommendations of 30s to 1min, to mediate an elevation in post-exercise serum growth hormone levels, have become untenable; no study has demonstrated greater muscle hypertrophy using shorter compared with longer rest intervals.

Novice vs. experienced vs. well trained vs. elite

Despite the above research, it is becoming increasingly important to differentiate between studies in novices, experienced or well trained and those regarded as elite. In this context, this continuum defines either strength and conditioning experience, normally recognised by measures of maximal strength, and/or level of sports performance and thus exposure to high-level environments and competitions (and associated stress). Many studies suggest a considerable difference between these levels of athletes, with the reported associations between T and physical performance best demonstrated in elite-trained athletes (Crewther et al., 2011). For example, Crewther et al. (2012) only found relationships between salivary free T concentrations and back squat (1RM; r = 0.92) and sprinting (10m; r = 0.87) performance in those who could squat double body weight – the reasons for this are likely multifaceted and covered throughout this chapter,

including via the dual-hormone hypothesis described below. Of note, the aforementioned correlations found above, are despite there being no difference in T concentrations between groups (i.e., 1RM $> 2.0 \times$ body weight vs. 1RM $< 1.9 \times$ body weight). Therefore, it may be that training background and strength levels are most important, as these are indicative of Type II fibre content and androgen receptor content, and infer enhanced motivation and risk taking behaviours, for example, these represent the enhanced ability to actually use free T. Therefore, more needs to be done to differentiate responses across populations, which may evolve into training paradigms that shift accordingly.

It is also important to consider individual responses to resistance training; this is especially the case when working with elite athletes. Pooling data (and thus presenting means only) can have an impact on both the validity of the results and the interpretation of study findings. For example, Beaven et al. (2008b) compared acute individual T responses of professional elite rugby players across commonly prescribed resistance training protocols (4 × 10 at 70%, 3 × 5 at 85%, 5 × 15 at 55%, or 3 × 5 at 40%). They showed an insignificant protocol effect on T concentration when considered as a homogenous group. However, when individual data among protocols were examined, a clear protocol-dependent effect was observed. Each individual athlete seemed to respond optimally, in terms of a T concentration increase, to one or two of the protocols, with minimal responses to the other protocols. Therefore, the protocol considered optimal in terms of anabolic response differed among individuals.

However, as aforementioned, changes in T do acutely influence training motivation, and thus load lifted and perhaps in this context, the ability to lift until true muscle fatigue across several sets. The at least pervasive effect of T on strength and hypertrophy is nicely surmised by Beaven et al. (2008a). They identified that (1) men show muscle growth at puberty when T production increases (Ramos et al., 1998); (2) aging men gradually lose muscle mass and strength, and exogenous application of T can reverse this (Anawalt & Merriam, 2001); (3) T replacement increases the fat-free mass and muscle size caused by hypogonadism (i.e., reduction or absence of hormone secretion or other physiological activity of the gonads) (Bhasin et al., 1997; Aleman et al., 2004); (4) exogenous application of supraphysiologic doses of T in men results in greater strength and muscle gains from resistance exercise (Bhasin et al., 1999; Strawford et al., 1999);

and (5) pharmacologic blockade of T-specific receptors suppresses exercise-induced hypertrophy of skeletal muscle (Inoue et al., 1994).

CORTISOL

Cortisol (C), a steroid hormone, is secreted from the adrenal cortex following stimulation from adrenocorticotrophic hormone (released by the anterior pituitary gland). The primary pathway for C secretion is through stimulation of the hypothalamus by the central nervous system as a result of hypoglycaemia, the flight or fight response, or exercise. Cortisol is considered a catabolic hormone to skeletal muscle tissue, and is released in response to low levels of glycogen; its primary role is to stimulate gluconeogenesis and glycogenolysis via glycogen, protein and lipid metabolism, and through its permissive actions on other hormones (e.g., catecholamines and glucagon). Although, if secreted over a prolonged period, it is generally considered detrimental to muscle mass, in short bursts it can actually facilitate subsequent anabolism. In this regard, it acts as a repartitioning hormone allowing energy to be re-distributed to where it is needed (e.g. a contracting muscle). It may also predict performance, similar to T (Crewther & Christian, 2010), and more recently, much like T, the effect C has on behavioural characteristics has been explored.

Cortisol concentration levels

Cortisol release response is similar to T and GH, whereby anaerobic metabolism acts as a potent stimulus (Ratamess et al., 2005). Therefore, despite chronically high levels of C reflecting adverse effects and progression towards overtraining, acute responses may be an essential part of the remodelling process, whereby the muscle must first be disrupted before it can adapt (Kraemer & Ratamess, 2005). It is, however, suggested that these acute training variables are varied to allow the adrenal gland to recover (secrete less cortisol) and prevent overtraining. Continued stress causes delayed recovery due to the over release of C and its negative effects exerted through gluconeogenesis and immune system depression (Kraemer et al., 2008).

The rise in GH and C concentrations during resistance training may also contribute to the regulation of glucose and glycogen metabolism (Samilios et al., 2003). Therefore, in strength-endurance type protocols (low load, high repetitions), the low tension applied for an extended period of time may cause hormonal responses in response to the activation of the anaerobic metabolism and the need for restoration of energy substrates (Samilios et al., 2003). It should be noted, however, that although bodybuilding type programmes evoke concurrent adaptations in both hormones, the magnitude of GH (and T) is greater than C, which may compensate for the negative effects (Samilios et al., 2003).

Circulating C levels reflect tissue remodelling and concurrent inflammatory responses (Kraemer et al., 1996). High levels of C (> 800 mmol/L) may signify an overtrained state (Fry et al., 1998), and have been highly correlated to serum creatine kinase concentration, which is a marker of muscle damage (Kraemer et al., 1993). In addition, the T:C ratio may provide a gross estimation (as both hormones have multiple functions across multiple tissue organs) of the anabolic/catabolic state of the body (Fry & Kraemer, 1997; Fry & Schilling, 2002). This has been positively related to performance (Alen et al., 1998), overreaching (Hakkinen et al., 1987) and overtraining (Stone et al., 1991). For example, McLellan et al. (2010) examined pre, during, and post-match neuromuscular and endocrine responses to competitive rugby league match play. Force–time data from the CMJ (including peak rate of force development, peak power and peak force) and saliva samples were collected to determine the T:C ratio and force output characteristics. Results revealed a return to normal T:C within 48 hours post-match, with neuromuscular function equally compromised for up to 48 hours after match play. These may indicate that a minimum period of 48 hours is required for neuroendocrine homeostasis post-competition.

Finally, T and insulin can counter the catabolic effects of C by blocking the genetic element in the DNA for C (Kraemer et al., 2008). However, this can only be achieved if they are bound to a greater number of receptors than C. Thus, after a period of training and endocrine adaptation, the effects of C may become less dramatic due to disinhibition of C by T (Kraemer et al., 2008). Resistance training experience of ≥ 2 years has been shown to be accompanied by increases in the T:C ratio (Hakkinen et al., 1998), and may be indicative of enhanced strength and training tolerance (Fry & Schilling, 2002).

Cortisol, behaviour and its moderating effect on testosterone

Cortisol may jointly work with T to moderate status-seeking behaviours (Cook & Crewther, 2014). This may be achieved via suppression of the hypothalamic-pituitary-gonadal-axis (and T secretion), inhibition of T actions on the target tissue and/or the down-regulation of the androgen receptors (Liening & Josephs, 2010). Similar to T, C responsiveness can vary in the presence of strangers or friends (Wagner et al., 2002). The acute neuroendocrine responses to social interactions have possible implications for modifying future performance and recovery, with transient changes in T and C levels linked to recovery from a competitive sport and/or subsequent match performance (Crewther & Cook, 2012; Cook & Crewther, 2012b). Therefore, controlling for situations that may challenge the stress tolerance of athletes, if not used purposefully, may hinder any sought-after training adaptations or performance gain.

The reported associations between T and physical performance tend to be best demonstrated in elite-trained athletes (Crewther et al., 2011). It is possible that these results might be less about a superior physical ability and more about a superior ability for performing under stress. For example, untrained individuals typically exhibit a larger neuroendocrine stress response (e.g., C) than trained individuals when exercising at the same workloads (Hackney, 2006). Behavioural studies explain that C may be moderating the effect of T (Mehta & Josephs, 2010; Mehta & Prasad, 2015) such that relationships are mostly positive at low C levels and negative at high C levels (Mehta & Prasad, 2015). For example, C can influence T activity or release via the motivational circuitry, psychological processing and feedback inhibition (Mehta & Prasad, 2015), supporting findings that T is positively related to dominance or aggression outcomes in men, but only when C levels are low (Mehta & Josephs, 2010; Mehta & Prasad, 2015).

These findings are applicable to sport and exercise, not only because muscle performance and dominance are linked (Gallup et al., 2007), but also because any exercise protocol deemed to be stressful may attenuate results. Currently only Crewther et al. (2016) have explored the moderating effect of C within this context. They examined the effect of C on the T relationship within handgrip strength; the men were assessed around a short bout of sprint cycling exercise (to create "stress"). The authors found that while T and C measures did not predict pre-test or resultant changes in

handgrip strength scores, a significant hormonal interaction was identified, such that T predicted both strength outcomes when taking into account individual differences in pre-test C levels. The direction of their relationships, however, was in contrast from the aforementioned. Specifically, pre-test T and handgrip strength were negatively associated in men with high pre-test C levels, and T and handgrip strength changes were negatively related in men with low pre-test C levels. The authors suggest that being less stressed (i.e., low C) might ensure that other potentiating mechanisms (e.g., myosin phosphorylation, motor unit recruitment) are activated by exercise (Tillin & Bishop, 2009), with a small or negative T response possibly indicating better tissue uptake (Crewther et al., 2011) and/or metabolite conversion (Wood & Stanton, 2012). Certainly further investigations are required into this mechanism which partly supports why inconsistent relationships are seen in men with little or no training experience, and why physiological elevations in T are not always necessary for muscle growth (Morton et al., 2016).

CONCLUSION AND PRACTICAL APPLICATION

For muscle hypertrophy, training programmes can utilise three sets of ten repetitions at or near 10RM loads, with short rest periods of no longer than one minute. This appears to maximally release anabolic hormones with blood lactate concentration seen as a causative factor. However, gaining research based momentum is the likelihood that actually three sets to failure, with rep ranges of 8–25, are just as effective. This appears to be due to motor unit recruitment rather than changes in hormone concentrations and load. Finally, seven sets of three repetitions (to failure) have also shown similar increases in hypertrophy, but this approach induces superior increases in strength. From a sports perspective, therefore, this may be the best volume load strategy.

Beyond hypertrophy, and pertinent to sports performance, is the effect that T demonstrates on the nervous system and behaviour. High levels appear to augment physical performance either directly or through motivational and perhaps risk taking means. The timing of training sessions (including for purposes of priming) and the effect of feedback, videos and “psyching up” interventions, in general, should therefore be explored to truly maximise both the training and competition performances.

Finally, it is important to acknowledge that more individualisation is needed when interpreting endocrinology research; this may be of particular relevance to elite athletes and very strong athletes. For example, the T release across commonly prescribed resistance training protocols differed greatly among professional athletes, suggesting that strength gain may be further enhanced by individuals adopting a periodisation model that predominately focused on the protocol that maximised their T response. The periodic measurement of hormones could therefore provide a method to ensure that the periodisation of resistance training is optimised for each individual athlete, also noting that athletes may, in time, change in their hormonal response to each resistance training protocol. Also, it may be that it is the increased androgen receptor content of very strong athletes that dictates the use of T, and perhaps interventions aimed at increasing T concentrations can not be realised until athletes can, for example, squat almost double body weight. Finally, it may be that it is an athlete's ability to tolerate stress, or perhaps not view a particular situation as stressful, that ultimately dictates the benefits that T has to performance – with or without a high androgen receptor content. The moderating effect of C may be such that high C levels ultimately override high concentrations of T. Again, environmental stimuli, athlete feedback and recovery strategies become central to this.

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CHAPTER 5

Training aerobic fitness

Alex Bliss and Rob Harley

SECTION 1 – INTRODUCTION

DEFINING AEROBIC FITNESS AND OTHER FREQUENTLY ENCOUNTERED TERMS

The physiological determinants of successful endurance sport performance have been considered for many years. Nobel prize winner A.V. Hill described endurance exercise in athletics and measured the contribution to performance by aerobic energy production pathways in the early 1920s. The maximal oxygen uptake was described as $\dot{V}O_2$ max and has continued to be considered an important performance determinant to the present day (Basset, 2002). However, a common issue in sports and exercise science is that the term "aerobic" is used to describe exercise in terms of duration, more so than the primary metabolic pathway for the activity. An "aerobic" effort is often used to describe long duration exercise, with the reverse being true of "anaerobic" efforts (Chamari & Padulo, 2015). In truth, dichotomising exercise into purely "aerobic" or "anaerobic" effort is not an accurate method by which to explain the physiological processes that are occurring. For example, at the end of a ramp-based $\dot{V}O_2$ max test (described below), a participant's blood lactate level will typically be above $8mmol{\cdot}L^{-1}$. Therefore, during this test of maximal oxygen uptake, a portion of the energy provided to achieve the exercise intensity required during the test has come from anaerobic energy pathways (anaerobic glycolysis).

To ensure consistency, and to encourage coaches and sports scientists working in applied practice to provide a clear message to their athletes, defining some of the common terminology encountered should help to improve practice (Chamari & Padulo, 2015). Therefore, prior to describing methods or strategies to train aerobic fitness, it is perhaps pertinent to carefully define what aerobic fitness is, and moreover, what it is not.

Aerobic fitness

Aerobic fitness, otherwise known as cardiovascular fitness, is a broad term, and encompasses the main physiological determinants of performance, as outlined below. In sport and exercise settings, measuring an athlete's

cardiovascular fitness is a key tool when establishing the credentials for upcoming performances and attempting to understand or explain previous performances. This is particularly so in sports where demonstrating superior aerobic fitness is a critical determinant in the performance and success of the athlete, most notably in sports performed above 80% of maximum heart rate and lasting longer than an hour.

Aerobic power

Technically, $\dot{V}O_2$ max is a measure of the *rate* of oxygen consumption (absolute = $L \cdot min^{-1}$. Relative to body mass = $mL \cdot kg^{-1} \cdot min^{-1}$) over a period of time. Therefore, a calculation of the maximal power generated by aerobic/oxidative pathways can be performed during a maximal oxygen uptake test involving the collection of expired air for gas analysis purposes. Individuals with high maximal aerobic power exhibit increased concentrations of aerobic enzymes, mitochondrial size and density, myoglobin, and capillary density, allowing for enhanced oxygen extraction at the muscular level (Tomlin & Wenger, 2001).

Aerobic capacity

Capacity, by definition, concerns the maximum amount that can be contained or produced. With regards to aerobic capacity, this is linked to the production of energy for exercise utilising aerobic metabolism pathways (MacInnis & Gibala, 2017). At maximal levels, this is often termed maximal aerobic capacity/maximal oxygen uptake ($\dot{V}O_2$ max) or peak aerobic capacity/peak oxygen uptake ($\dot{V}O_2$ peak). However, aerobic capacity is used as a term to identify blood lactate or ventilatory markers, such as maximal lactate steady-state (MLSS) or rate of work that can be sustained for extended periods of time, with increases in $\dot{V}O_2$ max and other aerobic capacity markers resulting from endurance training (Tomlin & Wenger, 2001; Ekblom et al., 1968).

PHYSIOLOGICAL DETERMINANTS OF ENDURANCE PERFORMANCE

Requirements from the various metabolic systems that produce energy within the human body during endurance running are dictated by the functions of race duration and race intensity (Boileau et al., 1982). Oxidative phosphorylation is the primary energy producing pathway in middle- and long-distance events. Therefore, athletes of national, international, or world-class level usually display well-developed aerobic fitness in a number of critical physiological performance parameters closely linked to oxygen uptake, namely:

1. the maximal oxygen uptake or $\dot{V}O_2$ max,
2. the amount of oxygen required to exercise at submaximal speeds (e.g., running economy),
3. the amount of oxygen required to maintain low blood lactate levels (lactate threshold, turnpoint) (Jones, 2007).

Models of endurance physiology from the mid 1990s to the end of the 21st century display these determinants of performance (and others), and they are inexorably linked to “performance velocity” (Coyle, 1995), “maximal velocity in races” (Basset and Howley, 2000), or “race pace” (Jones, 2006).

MEASURING AEROBIC FITNESS

$\dot{V}O_2$ max is the criterion measure of aerobic fitness and is considered to be the best single physiological variable for defining the function of the cardiovascular and respiratory systems (Cooke, 2009). However, the “gold standard” method for assessing aerobic fitness is to directly measure pulmonary gas exchange during exercise. This can be achieved using the Douglas bag method or by using breath-by-breath systems. For further information on these methods, readers are encouraged to read Jones (2007).

The measurement of the key determinants of aerobic fitness (see Table 5.1) can be conducted using various protocols. For endurance athletes, assessments will usually comprise a laboratory assessment of two parts: a “submaximal” test, used to establish blood lactate and ventilatory responses such as economy/efficiency, and a “maximal” test, used to establish the $\dot{V}O_2$ max. Both tests include multiple stages that will incrementally increase in speed or power output required. Stage duration for the submaximal

element of the assessment is usually three or four minutes, which is enough time to allow for "steady state" conditions to be achieved. This phase of the test is used to determine economy, lactate threshold, lactate turnpoint, and heart rate zones that can be used when prescribing training. The "maximal" test will involve shorter stage durations, but begin at a higher speed or power output and be performed until volitional exhaustion. The precision of these measurements has been shown to be around 3% and can be extremely useful in monitoring the effectiveness of training interventions (Jones, 2007).

TABLE 5.1 Operational definitions for frequently encountered terms. Adapted from Jones (2007)

Construct	*Acronym*	*Definition*
Lactate threshold	LT	The first "breakpoint" or "observable rise" in blood lactate levels where levels consistently exceed baseline (~1mmol·L^{-1})
Lactate turnpoint	LTP	The second "sudden and sustained" increase in blood lactate levels during incremental exercise. Approximate to MLSS.
Maximal lactate steady state	MLSS	The highest work rate at which blood lactate is elevated above baseline but remains stable. Blood lactate levels should not rise more than 1mmol·L^{-1} after 30 minutes exercise at the same work rate.
Onset blood lactate accumulation	OBLA	Blood lactate reference value of 4mmol·L^{-1}. The level at which, despite consistent work rate, the level of blood lactate will accumulate and continually rise over time.
Maximal oxygen uptake	$\dot{V}O_2$ max	The maximal rate of oxygen uptake. Identified by a plateau (or reduction) in $\dot{V}O_2$ despite increasing work rate.
Peak oxygen uptake	$\dot{V}O_2$ peak	The peak rate of oxygen uptake. Used in the absence of a plateau in oxygen uptake.
Velocity at $\dot{V}O_2$ max	v$\dot{V}O_2$ max	The velocity at $\dot{V}O_2$ max obtained by solving the regression equation describing measured $\dot{V}O_2$ at submaximal intensities and $\dot{V}O_2$ max.
Running economy	RE	The oxygen cost (or energy cost, see Shaw et al., 2015) of running at submaximal speeds or distances.

Athletes from other sports that require direct assessment of their aerobic fitness might undergo profiling as outlined above, although "sport-specific", field-based estimates, such as the yo-yo intermittent recovery or multistage fitness test, for example, might be utilised. These assessments sacrifice the

precision of measurement that can be obtained in a laboratory setting (although some laboratory equipment and techniques can be utilised in the field, e.g., portable gas/lactate analysers) in an effort to improve ecological validity. The number of sport-specific, field-based protocols for measuring or estimating aerobic fitness are too numerous to adequately capture here, but have been extensively outlined (Winter et al., 2007; Tanner & Gore, 2013).

SECTION 2 – TRAINING

PREFACE

This section is not designed to be prescriptive, but to outline evidence-based training methods and techniques that have been employed to bring about improved performance. In a recent editorial for the *International Journal of Sports Physiology and Performance* on the importance of "context", it was stated that: "there is such diversity across sports that it is important to consider the context of the individual athlete and environment… with decisions being made based on the sport, athlete level, training history, and so on" (McGuigan, 2016). Strength and conditioning scientists should be careful when extrapolating findings of research studies, particularly when using untrained participants, when giving advice to athletes and their coaches (Midgley et al., 2007). Coaches and scientists reading this chapter must carefully consider the complexities, nuances, and idiosyncrasies of their athlete(s) and their performance environment when applying any of the knowledge presented herein. If responsible for training prescription, they are encouraged to base their decision making processes around both evidence-based practice (from peer-reviewed scholarly journals, textbooks, etc.) and practice-based evidence (correspondence with their athlete[s] and their coach[es] or other practitioner peers). Over time, the strength and conditioning scientist will develop their own philosophy to training, based on the above, and should, through reflective practice and continued professional development, improve and adapt this philosophy to ensure they are creating a training environment that encourages positive adaptations for their athlete(s).

EXERCISE INTENSITY ZONES

Improving the physiological determinants of endurance performance requires careful manipulation of training volume (duration and frequency) and intensity. While volume is easily identifiable (by distance completed or time spent training), intensity of training effort is more difficult to classify. A common approach is to use blood lactate responses and corresponding heart rates to exercise at different intensities obtained through an

incremental ramp test. Seiler (2010) identified a three intensity zone model (Figure 5.1) based around the lactate threshold and ventilatory thresholds, while DiMenna and Jones (2016) have proposed a similar four zone model utilising intensity landmarks identified from a blood lactate profile. Seiler's (2010) zone 1 was classified as "low intensity training" (below lactate/ventilatory turnpoint 1 – also called lactate threshold) and referred to as "easy training" by DiMenna and Jones (2016). Zone 2 was classified as "threshold training", which describes the intensities between lactate threshold and lactate turnpoint/maximal lactate steady state, and referred to as "steady training" by DiMenna and Jones (2016). Zone 3, referred to as "high intensity training" (intensities above the lactate turnpoint/maximal lactate steady state), was broken down into two further zones by DiMenna and Jones (2016). The first is termed "tempo training", which describes continuous training performed at intensities just above the lactate turnpoint, usually performed for 20 to 30 minutes. The second is termed "interval training" which involves short, high-intensity bursts of activity from durations of six minutes down to 30 seconds performed with increasing intensity and shorter interval duration.

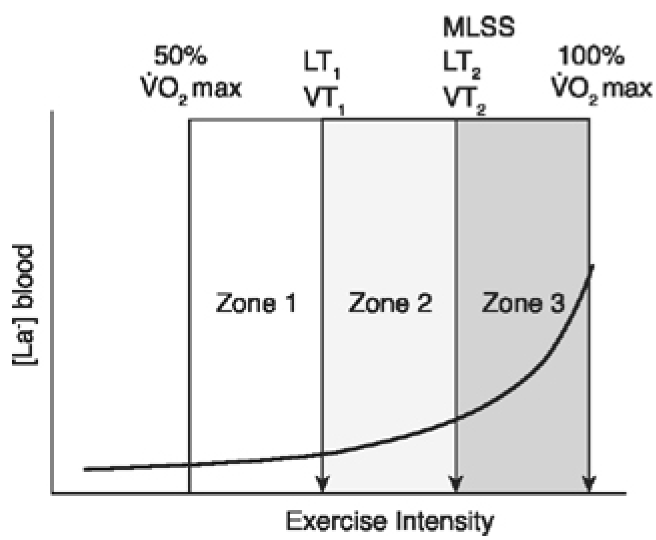

FIGURE 5.1 A three intensity zone model based on the identification of ventilatory or blood lactate thresholds (Seiler, 2010).

LOW-INTENSITY/EASY TRAINING (BELOW LACTATE THRESHOLD)

This intensity of training is usually implemented as easy recovery sessions and to allow athletes the opportunity to accumulate large training volumes, and usually performed as bouts of greater than 30 minutes. High training volumes and number of years' running experience have been suggested to be important for improving running economy (Morgan et al., 1995; Midgley et al., 2007). While being appropriate for distance athletes, its applicability for athletes who partake in repeated sprint activity sports is limited. Endurance athletes have been shown to spend around 80% of their training time in this zone (Seiler & Tønneson, 2009).

THRESHOLD/STEADY TRAINING (BETWEEN LACTATE THRESHOLD AND LACTATE TURNPOINT)

This type of training is especially important for endurance athletes as it is felt that the accumulation of mileage over a prolonged period of time helps improve running economy. Jones (2006) reported that Paula Radcliffe's running economy improved by 15% between 1992 and 2003, the largest improvements occurring at speeds where an individual undertakes the largest proportion of their training. Training at intensities below the lactate turnpoint are usually performed over distances of 5 to 15 miles. If coaches have not got access to laboratory data in determining speeds and heart rates that correspond to these training zones, a simple coaching cue of "comfortably hard" could help athletes achieve the correct intensity (see Figure 5.2 and Table 5.2). In the authors' experience, this has proved especially useful when working with games players during the off-season due to their unfamiliarity with this form of training. Exercising above the lactate turnpoint will feel more physically demanding, and the corresponding coaching cue of "hardly comfortable" should help athletes internalise how they should be feeling during tempo and interval type training.

TEMPO AND HIGH-INTENSITY TRAINING (ABOVE LACTATE TURNPOINT/MAXIMAL LACTATE STEADY STATE)

Typically, periodised training programmes of highly trained endurance athletes will involve more continuous, low-intensity, high-volume type training early in the season, with short duration, high-intensity training undertaken as the athlete enters their pre-competition and competition training phases (Laursen & Jenkins, 2002). The rationale behind utilising this training method is that increases in volume alone do not appear sufficient to improve the key determinants of endurance performance, other than running economy (Laursen & Jenkins, 2002). Esfarjani & Laursen (2007) showed that moderately trained athletes, training at velocities equivalent to 100% and 130% of the velocity at $\dot{V}O_2$ max (v$\dot{V}O_2$ max) led to significant improvements in v$\dot{V}O_2$ max, $\dot{V}O_2$ max, and 3000m time trial performance. The findings in recreationally active and moderately trained athletes also appear to extend to well-trained populations. Enoksen et al. (2011) demonstrated that in 10 weeks, well-trained middle-distance runners improved v$\dot{V}O_2$ max velocity at lactate threshold, and running economy when adopting a high-intensity, low-volume training programme, as where their matched high-volume, low-intensity training group improved their running economy only. The runners were training six times per week, completing mean training mileages of > 90km per week, and had mean $\dot{V}O_2$ max values > 70 $mL \cdot kg^{-1} \cdot min^{-1}$. The high-intensity group completed 33% of training at a heart rate higher than 82% of maximum, with the low-intensity group completing 13% of total training volume in the same range. However, it appears that the dose-response relationship for high-intensity interval training needs to be carefully considered with highly-trained athletes. Menz et al. (2015) found that 11 sessions of high-intensity interval training that elicited heart rate responses between 88% and 94% of maximum heart rate did not significantly affect $\dot{V}O_2$ max when compared with a control group. The most likely explanation for the lack of meaningful change was the short duration of the programme (three weeks) resulting in a chronic stimulus that was insufficient to promote physiological adaptation. Although other studies employing the same exercise regimen (four repetitions of four minutes or “4x4”) had demonstrated significant improvements in $\dot{V}O_2$ max in four weeks (Helgerud et al. 2007), the participants had markedly lower starting maximal aerobic power values than those of the Menz et al. (2015) study (58.1 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$ vs. 63.7 ± 7.7 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively). This led the authors to conclude that, in line with other work, lower $\dot{V}O_2$

max values at baseline and changes to $\dot{V}O_2$ max are significantly correlated (Menz et al., 2015). Coaches and scientists should, therefore, consider the dose-response relationship when introducing high-intensity interval training with athletes, and on the balance of evidence, expect highly-trained athletes to respond more slowly to this type of training intervention than recreationally active or moderately-trained athletes.

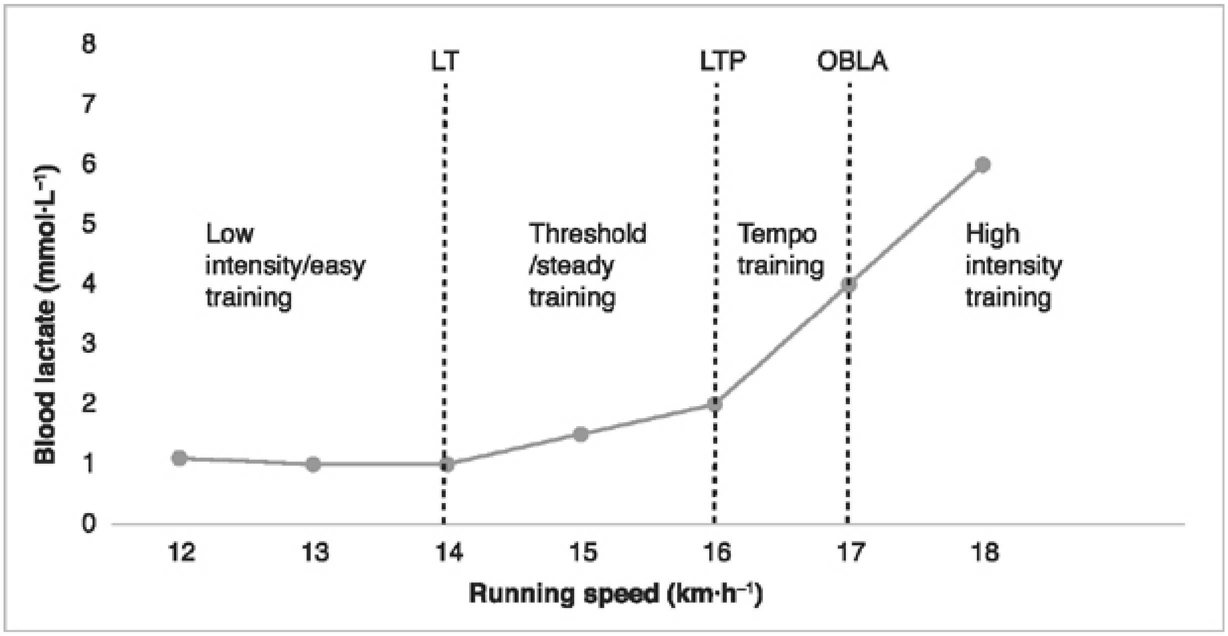

FIGURE 5.2 Example blood lactate response to incrementally increasing running speed with corresponding training zones and physiological markers.

TABLE 5.2 Table of training zones and cues that can be used by athletes and coaches to estimate their current zone. With laboratory assessment, training zones and corresponding intensities can be based on blood lactate levels and the corresponding heart rate at that level to obtain an objective, easily monitored method to allow for training in the desired zone

Training zone	*Typical blood lactate range (mmol·L^{-1})*	*Coaching cue*	*Breathing reference*
Low intensity/easy	~1	Very easy or easy	Very easy or easy to talk while exercising
Threshold/steady	1 (or higher than baseline)–3	Comfortably hard	Ok to talk
Tempo	3–4	Hardly comfortable	Hard to talk
High intensity	>4	Hard to maximum effort	Cannot talk

STRENGTH TRAINING AS PART OF A STRATEGY FOR IMPROVING AEROBIC FITNESS

Historically, endurance training methods aiming at improving markers of aerobic fitness and strength training have been viewed as separate entities, with the traditional view being that improvements in aerobic fitness result from endurance training only (Yamamoto et al., 2008). Combining strength training with endurance training aimed at improving aerobic fitness (often referred to as concurrent training, discussed in more detail in Chapter 7) has been suggested to impair muscular hypertrophy and has been termed "the interference effect" (Hickson, 1980). Endurance athletes are often reluctant to engage with strength training through concerns over muscular hypertrophy, consequential increases in body mass, and perceived questionable specificity of the exercises undertaken (Crane, 2011). Other concerns expressed include delayed onset muscle soreness and decreased capillary density and mitochondrial function (Yamamoto et al., 2008).

The issue of compatibility appears well grounded in physiological and resistance training theory, as it is known that strength and endurance training operate at different ends of the physiological energy systems spectrum (Jones et al., 2013). At the molecular level, following a bout of strength training, there is a sustained increase in the activity of mammalian target of rapamycin (mTOR) which helps to up-regulate protein synthesis and critically underpins improvements in muscle strength and size (Baar, 2014), which are key goals of this type of exercise. Following endurance training, there is increased activation of the adenosine-monophosphate-activated protein kinase-peroxisome proliferator-activated receptor gamma coactivator (AMPK-PCG 1α) pathway which inhibits mTOR and therefore leads to diminishing protein accretion (de Souza et al., 2014). Despite the above concerns, research has shown that the combination of a variety of strength training modalities with endurance or aerobic fitness training can bring about performance benefits (Bonacci et al., 2011; Beattie et al., 2014; Beattie et al., 2017).

Traditional, heavy-resistance strength training enhances performance through stimulating adaptations in muscle cross-sectional area, or hypertrophy (Paavolainen et al., 1999). Classically, strength training is introduced into an athlete's programme to bring about changes in muscle cross-sectional area (hypertrophy) and to improve force generation

properties of the muscles targeted. There are three main types of strength training: maximal strength, explosive strength (strength-speed and speed-strength), and reactive strength, each of which can be identified by the velocity of movement (Siff, 2003). It has been suggested that in order to provide the most functionally relevant and performance enhancing training for endurance athletes, the resistance training element should focus around explosive and reactive type exercise. Developing high levels of explosive-strength (also referred to as rate of force development) and subsequently high external mechanical power are thought to be two of the most important characteristics for a wide range of sporting performance (Suchomel et al., 2016). Sports performers that particularly benefit from high levels of explosive-strength are those that are required to jump, rapidly change direction, or, as in the case with sprint and short-middle-distance athletes, are required to sprint maximally (Haff & Nimphius, 2012). Paavolainen et al. (1999) investigated the use of simultaneous endurance training and explosive strength training, consisting of various sprints, jumps, and low-load, high-movement velocity resistance training, including leg press and leg extension exercises, on 5km running performance. They demonstrated an improvement in 5km time trial in well-trained endurance athletes without changes in maximal oxygen uptake. However, before explosive-strength can be developed, the scientific literature suggests that high levels of muscular strength must form the foundation on which high rates of force development and external mechanical power can be built (Suchomel et al., 2016), as well as to reduce injury risk (Beattie et al., 2014).

In addition to the rationale above, well-trained elite athletes are unlikely to be able to significantly alter their maximal oxygen uptake (Jones, 1998). Therefore, strength training has been proposed as a method by which performance in endurance events can be improved, as such training demonstrated beneficial effects on running economy, muscular power, and neuromuscular function (Paavolainen et al., 1999, Beattie et al., 2014; Beattie et al., 2017).

THE ROLE OF AEROBIC FITNESS IN REPEATED SPRINT ACTIVITY SPORTS

The duration and intensity of sporting activity will dictate the importance of aerobic energy contribution and the types of aerobic fitness required for optimal performance. It is commonly recognised that the longer the duration and the higher the intensity of sporting activity the more influence levels of aerobic fitness will have on performance. A number of team sports, along with racquet sports, involve high-intensity activity interspersed with moderate to low-intensity activity, and are commonly referred to as repeated sprint activity sports. Although the exact aerobic contribution for peak performance in these sports and, therefore, the aerobic fitness levels which are required for high level performance will vary, and are often a cause for discussion, the importance of aerobic fitness, and its constituent parts, to help maintain a high work rate is of paramount importance. The interplay and link between increases in aerobic fitness components and increases in performance has been clearly demonstrated in a variety of sports. Helgerud et al. (2001) reported that elite junior soccer players (mean age 18.1 years and over eight years' playing experience) were able to improve their soccer performance as indicated by a 20% increase in distance covered in the match, 100% increase in the number of sprints performed, 24% increase in the number of involvements with the ball, as well as players being able to perform at a higher work intensity (85.6% of max heart rate rather than 82.7%) following two sessions of interval training per week, consisting of 4x4 minutes at 90–95% max heart rate with a 3 minute active recovery, in addition to their regular training for eight weeks. This improvement in performance was facilitated by improvements in all three components of aerobic fitness with $\dot{V}O_2$ max significantly increasing from 58.1 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$ to 64.3 ± 3.0 $mL \cdot kg^{-1} \cdot min^{-1}$ ($P<0.05$), lactate threshold increasing from 47.8 ± 5.3 $mL \cdot kg^{-1} \cdot min^{-1}$ to 55.4 ± 4.1 $mL \cdot kg^{-1} \cdot min^{-1}$ ($P<0.05$), and running economy improving by 6.7% ($P<0.05$). Although the distances covered and the duration of playing time is significantly less for a basketball match than a soccer match, Ben Abdelkrim et al. (2009, 2010) has provided evidence to support the importance of basketball players possessing a good level of aerobic conditioning. The authors demonstrated that the amount of high-intensity activity that was performed during the second and fourth quarters significantly dropped while blood metabolites significantly increased, indicating increasing levels of fatigue in the later stages of basketball matches.

USING SMALL-SIDED GAMES TRAINING TO IMPROVE AEROBIC FITNESS FOR REPEATED SPRINT ACTIVITY SPORTS

As mentioned earlier, the aerobic energy contribution and, therefore, the importance of aerobic fitness for a variety of repeated sprint activity sport athletes, will vary depending upon the duration and intensity of those sports. Strength and conditioning coaches need to develop an understanding of the energy demands required in their sport in order to target the energy systems employed. A detailed discussion of the acute training variables that can be implemented to enhance repeated sprint ability is outlined in Chapter 6. This section will focus on the literature and practice related to the employment of small-sided games to improve aerobic fitness, technical ability, and enjoyment. Small-sided games in a variety of repeated sprint activity sports (e.g., soccer, rugby, handball, basketball) have been demonstrated to elicit appropriate levels of physiological overload in order to improve and/or maintain aerobic fitness parameters (Impellizzeri et al., 2006; Buchheit et al., 2009; Halouani et al., 2014). The use of small-sided games as conditioning sessions also requires players to employ sports-specific skills and movement patterns (e.g., changes of direction), and exposes players to competitive situations, forcing them to play under pressure and in a fatigued state.

Impellizzeri et al. (2006) demonstrated that small-sided games of soccer can be used as an effective training mode to enhance aerobic fitness and match performance. They used 40 junior soccer players (mean age 17.2 ± 0.2 years with nine years playing experience) and allocated them to either an aerobic interval running group or a small-sided game group. Two sessions per week of their regular training were conducted in this mode of activity. The aerobic interval training programme design consisted of four bouts of 4 minutes running around a soccer pitch at 90–95% max heart rate, with 3 minutes active recovery (60–70% maximum heart rate), which has previously been demonstrated by Helgerud et al. (2001) to improve aerobic parameters and game playing performance. The small-sided games ranged from 3 vs. 3 to 5 vs. 5 and were implemented with the same time intervals as the running group. To negate any decline in work intensity, replacement balls were always available should a ball be kicked out of the playing area. The average exercise intensity as expressed as a percentage of maximum

heart rate during the small-sided games was not different from that reached in the interval running sessions (91.3 ± 2.2% vs. 90.7 ± 1.2%, respectively). Significant improvement in aerobic power and capacity occurred in both intervention groups. $\dot{V}O_2$ max significantly improved from 55.6 ± 3.4 to 60.2 ± 3.9 $mL\cdot kg^{-1}\cdot min^{-1}$ for the running intervention group and 57.7 ± 4.2 to 61.6 ± 4.5 $mL\cdot kg^{-1}\cdot min^{-1}$ for the small-sided games group. It is interesting to note that most of this improvement was made in the first four weeks during pre-season training with no significant improvement taking place over the next eight weeks. The speed at lactate threshold also significantly improved over the twelve week intervention from 11.2 ± 0.6 to 12.2 ± 0.4 $km\cdot h^{-1}$ for the running interval group and 11.3 ± 0.7 to 12.4 ± 0.5 $km\cdot h^{-1}$ for the small-sided games group. Interestingly, the time course for this change was slightly different with velocity and $\dot{V}O_2$ at the lactate threshold improving a further 5% from mid- to post-training, unlike the aerobic power data indicating that the time course for adaptations to this component of aerobic fitness may take longer than those associated with changes in aerobic power. Finally, a 13% improvement in the time to complete Ekblom's soccer specific endurance circuit (Balsom, 1994) was reported as occurring during the first four weeks of training with no further improvement during the subsequent eight weeks of training.

It is clear to see that training involving technical elements (i.e., small-sided games) can be used as effectively as running interval training to improve aerobic parameters which impact upon soccer performance. However, given the task-specific nature of small-sided games (short sharp changes of direction, jumping, lateral running, etc.) which are replicated in Ekblom's endurance circuit, Impellizzeri et al. (2006) did comment that contrary to their hypotheses, the small-sided games group did not achieve superior performance enhancements compared with the running interval group. In their conclusions they suggest that using small-sided games increased players' motivation and made high-intensity training more acceptable. This hypothesis has recently been tested by Los Arcos and colleagues (2015) who used a Physical Activity Enjoyment Scale (Motl et al., 2001) to demonstrate that small-sided games promoted considerably higher physical enjoyment scores than the interval running sessions ($P<0.05$). Unlike the study by Impellizzeri et al. (2006), the intervention took place during the last six weeks of the season, when studies have previously reported declines in aerobic fitness (Gravina et al., 2008,

Caldwell et al., 2009, Tønnessen et al., 2013). Motl et al. (2001) reported that the change in maximal aerobic speed over the six week period (16.8 ± 0.9 to 17.1 ± 1.0 $km \cdot h^{-1}$ and 17.0 ± 0.8 to 16.9 ± 0.8 $km \cdot h^{-1}$) was not significantly different (1.7 ± 1.5%, $P<0.05$ and –0.4 ± 1.9%, $P<0.05$) for interval training vs. small-sided games, respectively, and concluded that the small-sided games were as effective as interval training in maintaining aerobic fitness. Clemente et al. (2014) has recently proposed methodological guidelines for the organisation of small-sided soccer games, categorising them based upon the game structure and pitch dimensions and how this will influence the acute training variables of intensity, repetition, duration, recovery, and volume.

Similar evidence supporting the use of small-sided games to enhance aerobic fitness has been demonstrated in rugby by Gabbett (2006), who implemented a nine week in-season training study comparing the use of either two traditional conditioning sessions (e.g., repeated short-duration, high-intensity running activities with no skilled component) to two skills-based conditioning games (with modified rules and modified field size) in addition to the athletes' regular training sessions. Although over the nine weeks the week-by-week training load varied, the total training load, assessed using Foster's sessional RPE (Foster et al., 2001), for all the sessions undertaken for both conditions were not significantly different. $\dot{V}O_2$ max assessed using the multistage shuttle run test was shown to significantly increase for both the traditional conditioning (49.6 ± 0.7 to 52.2 ± 0.5 $mL \cdot kg^{-1} \cdot min^{-1}$, $P<0.05$) and the skills-based conditioning games groups (46.6 ± 0.5 to 48.8 ± 0.4 $mL \cdot kg^{-1} \cdot min^{-1}$, $P<0.05$). It is interesting to note that significant improvements in 40 metre sprints and vertical jump ability also occurred in the skills-based conditioning group but not in the traditional training group.

Strength and conditioning coaches are encouraged to work closely with skills-based coaches in the development and implementation of appropriate small-sided games to help enhance and maintain aerobic fitness while affording the additional physical and technical benefits discussed in this chapter.

CONCLUSION

The prioritisation of aerobic fitness training is a complex area and will depend upon many variables, from the aerobic demand of the athlete's sports performance to the stage of the season the athlete is currently performing in. Although selecting training zones and the amount of time an athlete should spend training in that zone is still a contentious issue, the evidence to support the use of high-intensity training for improving the aerobic fitness of athletes who partake in repeated sprint activity sports is growing. Readers are directed to Chapter 6 on repeated sprint activity and high-intensity training for guidance on prescription, and are encouraged to explore the implementation of small-sided games to afford the benefits described previously. The use of strength training as a method to aid aerobic fitness development should also be considered by coaches working with well-trained endurance athletes.

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CHAPTER 6

Repeat sprint ability and the role of high-intensity interval training

Anthony Turner and David Bishop

INTRODUCTION

Many sports involve frequent bursts of high-intensity movements interspersed with brief recovery intervals (consisting of complete rest or low- to moderate-intensity activity) over an extended period of time (one to four hours) (Bangsbo et al., 1991; Faude et al., 2007; Girard et al., 2008; Glaister, 2005; Spencer et al., 2005). Therefore, the ability to recover and to reproduce performance during subsequent high-intensity efforts is probably an important fitness requirement of athletes engaged in these disciplines, and has been termed repeated-sprint ability (RSA) (Bishop et al., 2001; FitzSimons et al., 1993). While many different types of training have been proposed to improve RSA, high-intensity interval training (HIIT) has been suggested as a means of developing many of the factors contributing to RSA (Bishop et al., 2011). Given the apparent importance of HIIT for developing RSA, it is fundamental that strength and conditioning coaches have a thorough understanding of how to programme HIIT to best achieve improvements in RSA. Therefore, the aims (and order) of this chapter are: (1) discussing the interaction between sprint intervals (duration and frequency) and metabolic energy supply, (2) identifying various approaches to HIIT programming – the reader should be able to rationalise the use of each given the aforementioned, and finally, (3) discuss RSA testing that can then be used to judge the efficacy of training.

THE BIOCHEMISTRY OF REPEATED SPRINTS

Repeated-sprint ability requires both a high maximal sprint power and the ability to maintain high maximal power during each subsequent sprint. A high maximal sprint power is related to the ability to deplete large amounts of high-energy phosphates at a fast rate. The human muscle stores ~3 25 mmol/kg dry muscle (dm) of adenosine triphosphate (ATP). With a peak ATP turnover rate of ~15 mmol/kg dm/s, that's enough to fuel one to two seconds of maximal work (Gaitanos et al., 1993). Therefore, from a metabolic perspective, power is dictated by the amount and rate at which ATP is synthesised and then hydrolysed. ATP is never actually fully depleted (as it is used for basic cellular functioning too), but depleted by 45% in a 30s sprint (Boobis et al., 1982) and between 15% and 30% in a 10s sprint (Jones et al., 1985). As ATP stores are broken down, various metabolic pathways (energy systems) collaborate to resynthesise ATP in an attempt to maintain peak rates of ATP turnover. As the brief recovery times between repeated sprints will lead to only a partial restoration of energy stores, the amount of ATP resynthesised is likely to be an important determinant of the ability to maintain high maximal power during each subsequent sprint. With respect to the energy systems used to resynthesise ATP, there is a trade-off between power and capacity. The contribution of each energy system is determined by exercise intensity, bout frequency, and the duration of the rest period. The energy systems are Phosphocreatine (PCr), anaerobic glycolysis, and the aerobic/oxidative system; these are briefly discussed in the next sections.

PCr

There are ~ 80 mmol/kg dm of PCr stored in the muscle (Gaitanos et al., 1993) – around three times the amount of ATP – and with a turnover rate of ~ 9 mmol ATP/kg dm/s (Hultman & Sjöholm, 1983), PCr stores are largely depleted within 10s of sprinting (Glaister, 2005). The PCr system has the fastest ATP turnover rate of all energy systems, as there is only one enzymatic reaction (compared to the nine that occur with glycolysis, for example). As with ATP, and because of the contribution made by the other pathways, PCr is not normally depleted. For example, during all-out efforts, PCr is only depleted by 60–80% over 30s (Boobis et al., 1982), 40–70%

over 10s (Jones et al., 1985), 30–55% over 6s (Boobis et al., 1982) and 25% over 2.5s (of electrical muscle stimulation) (Hultman & Sjöholm, 1983); these results suggest that the ATP for a short sprint is also heavily subsidised by anaerobic glycolysis.

Because the recovery of power output maps the time course of PCr resynthesis (Bogdanis et al., 1995; Sahlin & Ren, 1989), and is attenuated by creatine supplementation (Mujika et al., 2000), PCr availability is likely to be a major factor governing the ability to repeat a maximal sprint effort (Glaister, 2005). PCr is resynthesised by the aerobic system within the mitochondria, via the creatine shuttle, and requires one molecule of ATP. Given this cost, restoration happens when energy requirements are low, such as during rest periods. As such, the contribution of PCr to subsequent sprints is governed by the length of the rest period; PCr resynthesis occurs at around 1.3 mmol/kg dm/s (Gaitanos et al., 1993). Approximately 85% of PCr stores are restored in two minutes, 90% in four minutes, and 100% in eight minutes (Harris et al., 1976; Hultman et al., 1967). Furthermore, recovery only happens when the blood supply to the working muscle is not occluded, which in turn is suggestive of why an active recovery between bouts is important (and may expedite PCr resynthesis). For example, an active recovery (vs. passive) consisting of cycling at sub-maximal intensities significantly increased peak power using 8 x 6s cycle sprints with 30s of rest (Signorile et al., 1993). In addition to aiding PCr resynthesis, the active recovery may reduce muscle acidosis by speeding up the removal of hydrogen ions (H^+) and lactate from the working muscles; this would also increase lactate's use as a fuel source (Signorile et al., 1993).

Adaptations that aid the resynthesis of ATP by the PCr system likely result from increases in the enzymes creatine kinase and myokinase (the latter catalyses the phosphorylation of two adenosine diphosphate [ADP] molecules to ATP and adenosine monophosphate [AMP], and adaptations to the aerobic system such as increased blood flow and mitochondrial biogenesis.) For example, Bishop et al. (2008) reported improvements in PCr resynthesis following a HIIT protocol of 6–12 × 2min reps at ~ $\dot{V}O_2$max, with 1min rest periods. Adaptations here were attributed to improvements in aerobic fitness, in either $\dot{V}O_2$max or the rate of PCr resynthesis. This was in contrast to 8 x 30s reps at ~ 130% $\dot{V}O_2$max, with

90s rest periods, where no change was found. There is, however, limited research investigating the effects of different types of training on PCr resynthesis.

ANAEROBIC GLYCOLYSIS

During brief maximal sprints, the rapid drop in PCr stores is offset by increased activation of glycolysis and glycogenolysis; the former relating to the breakdown of glucose from the blood stream and the latter the breakdown of glycogen in the cytoplasm. The maximal turnover rate of ATP production via these pathways is around ~ 8 mmol/kg dm/s (Gaitanos et al., 1993; Hultman & Sjöholm, 1983; Jones et al., 1985; Parolin et al., 1999). This system involves multiple enzymatic reactions, so is not as fast as the PCr system, but collectively they maintain an ATP turnover rate of ~ 12 mmol/kg dm/s (Boobis et al., 1982; Gaitanos et al., 1993). Glycolysis uses one ATP, as glucose must first be converted into glucose 6-phosphate via the hexokinase reaction once it enters the cytosol; this point should emphasise the importance of starting competitions in a fully glycogen loaded state. The rapid onset of anaerobic glycolysis with maximal work can be noted by studies that report high values of lactate (> 4 mmol/L) within 10s (Boobis et al., 1982; Jones et al., 1985). Surprisingly, values as high as 40 mmol/kg dm have been recorded after just 6s of sprint cycling (Dawson et al., 1997).

Following different types of training, adaptations to this system include increases in the enzymes phosphorylase, phosphofructokinase (PFK), and pyruvate dehydrogenase (PDH). PFK is considered the regulatory enzyme here, responding to increased cellular levels of AMP and inorganic phosphate (P_i), as would be expected at the start of a sprint. Increases in PDH activity ensures that pyruvate production is more closely matched to oxidation, thus increasing Acetyl-CoA provision for the tricarboxylic acid (TCA) cycle. This is an important adaptation to RSA, as it means less production of lactate acid, or rather, the accompanying increases in H^+. Training-induced changes in phosphorylase and PFK are likely greater using intervals that stimulate maximal accumulated oxygen deficit (Bishop et al., 2011), for example, training that involves repeated 30s bouts (Bogdanis et al., 1995). Furthermore, greater rest durations appear needed

(> 4min) to ensure a maximally high intensity of work, and thus maximal stimulation of glycolytic enzymatic activity.

With intramuscular stores of around 400 mmol/kg dm (Gaitanos et al., 1993), glycogen availability is not likely to majorly compromise ATP provision during the repeated sprints typically used during investigatory studies (Glaister et al., 2005). Instead, it may be the progressive changes in metabolic environment (as noted by the aforementioned high lactate values) that ultimately cause a reduction in ATP provision via this system. For example, Gaitanos et al. (1993), using 10 x 6s sprints with 30s rest periods, found that the first sprint produced ATP using 50% PCr and 44% glycolysis, while the tenth sprint used 80% PCr and 16% glycolysis; this was accompanied by a 27% loss in power output, an 11 mmol/L increase in muscle lactate, and a significant drop in ATP production rate. In such scenarios, noting the relatively forgiving W:R (work to rest ratio) of Gaitanos et al. (1993), the shortfall in energy is thus provided by the aerobic system.

Hydrogen ion flux and buffer capacity

The anaerobic conversion of pyruvate yields lactate and H^+. Lactate, however, is not the cause of fatigue and can be used as an energy substrate. For this, lactate is transported in the blood to the liver, referred to as the Cori cycle, and converted into glucose. Instead, the H^+ accumulation decreases intracellular pH, which in turn has been reported to inhibit oxidative phosphorylation and the activity of glycolytic enzymes (such as PFK), as well as the binding of calcium to troponin and thus muscle excitation-contraction coupling (Nakamaru & Schwartz, 1972). Therefore, the removal of H^+ from skeletal muscle is likely to be of importance for the ability to sustain repeated sprints (Pilegaard at al., 1999). For example, while the trained and untrained may have similar release rates of lactate and H^+ during intense exercise, the intracellular-to-interstitial gradients of these are lower in the trained population (Sahlin & Henriksson, 1984). Combined, these results suggest a trainable muscle buffer capacity that may be important to RSA performance.

The transient nature of the physiological pH (i.e., 7.4), which is affected by changes in H^+, is governed by a series of buffering mechanisms. These attenuate the effects of H^+ on metabolism by removing H^+ when the pH

declines (creating an acidic environment) and by releasing H^+ when the pH increases. There are both intracellular (i.e., protein and phosphate groups) and extracellular (i.e., proteins, haemoglobin [Hb], and the bicarbonate pool) buffers. As the H^+ diffuses out of the muscle into the blood, it is buffered by bicarbonate (via the bicarbonate buffering system), thus attenuating changes in plasma pH by shifting the chemical equilibrium according to Le Chatelier's principle. For example, any excess H^+ will associate with bicarbonate forming carbonic acid, thus resulting in a smaller net increase in acidity. The reaction is illustrated in Equation 6.1. This buffering system is further facilitated by an increase in respiration rate to remove excess CO_2 and thus acidity. Interestingly, one of the reasons you vomit during high-intensity training is that this provides the quickest means to remove large amounts of acid – the stomach is full of hydrochloric acid. In a similar way to bicarbonate, phosphate ions (see Equation 6.2) and carnosine act as intracellular buffers. Carnosine is a dipeptide formed of two amino acids, beta-alanine and histidine, with the former often regarded as an ergogenic aid to HIIT type activities (Artioli et al., 2010). Similarly, supplementation with sodium bicarbonate can be beneficial (Bishop et al., 2004a), as is a combination of both (Tobias et al., 2013).

Bishop et al. (2004a) have shown that muscle buffer capacity (calculated in vivo from the ratio of blood lactate to changes in pH and as per Equation 6.3) and RSA (5 x 6s cycle sprints, departing every 30s) are significantly correlated ($r = 0.72$, $n = 23$); this relationship with RSA was actually higher than that for $\dot{V}O_2$max and LT (r = 0.60 and 0.55, respectively). Further, Edge et al. (2006) have shown that increases in buffer capacity are intensity dependent. In two groups matched for volume and showing similar improvements in $\dot{V}O_2$max and LT post training, only the high-intensity group (working at 120–140% LT) significantly improved buffer capacity. Improvements in buffer capacity are also attributable to improvements in the sarcolemmal lactate/H^+ transport capacity as well as an enhanced content of monocarboxylate transport proteins (MCT1 and MCT4) (Pilegaard et al., 1999).

Equation 6.1

Where CO_2 = carbon dioxide, water = H_2O, carbonic acid = H_2CO_2, hydrogen = H^+, and bicarbonate = HCO_3^-.

$CO_2 + H_2O \leftrightharpoons H_2CO_3 \leftrightharpoons HCO_3^- + H^+$

Equation 6.2

HPO_4^{2-} = hydrogen phosphate, H^+ = hydrogen, and PO_4^{3-} = phosphate.

$HPO_4^{2-}\ H^+ + PO_4^{3-}$

Equation 6.3

Calculation of buffer capacity (β), where Δ = change and La^- = lactate (Sahlin & Henriksson, 1984).

$\beta = \Delta\ [La^-)]_i\ /\Delta\ pH_i$

AEROBIC METABOLISM

Unlike the anaerobic production of ATP that occurs in the cytoplasm of the cell, oxidative production occurs in the mitochondria. Here, pyruvate (via PDH) is converted to acetyl coenzyme A (rather than lactic acid), where it enters the TCA cycle and then the electron transport chain, before yielding 28 moles of ATP (vs. one from the PCr system, 2 from glycolysis, and 3 from glycogenolysis). This system contributes to ATP provision sooner than commonly believed. For example, during the first 6s of a 30s maximal sprint (Parolin et al., 1999), or the first 5s of a 3min intense bout (> 120% $\dot{V}O_2max$) (Bangsbo et al., 2001), an ATP turnover rate of ~ 1 mmol ATP/kg dm/s was hypothesised; this contributed ~ 10% of total energy produced. Also, as sprints are repeated, the $\dot{V}O_2$ of successive sprints will increase (Gaitanos et al., 1993; Spencer et al., 2005) if recovery periods are not sufficient to resynthesise PCr, oxidise lactate, or remove accumulated intracellular Pi (through ADP phosphorylation via myokinase). For example, McGawley & Bishop (2015) investigated the $\dot{V}O_2$ during the first and last sprints during two, 5 × 6s repeated-sprint bouts separated by passive rest, such that work done between each bout was the same. These investigators sought to assess the influence made by oxidative metabolism on RSA, hypothesising that reductions in fatigue and improved sprint times would be related to markers of aerobic fitness. Across both bouts, the $\dot{V}O_2$

during the first sprint was significantly less than the last sprint ($p < 0.001$), the estimated aerobic contribution to the final sprint (measured in k J) was significantly related to $\dot{V}O_2$max ($r = 0.81$, $p = 0.015$ and $r = 0.93$, $p = 0.001$, respectively) and finally, the $\dot{V}O_2$ attained in the final sprint was not significantly different from $\dot{V}O_2$ max ($p = 0.284$ and $p = 0.448$, respectively). The authors thus concluded that given the continuous increases in $\dot{V}O_2$ across sprints, $\dot{V}O_2$ max might be a limiting factor to performance in latter sprints. However, while $\dot{V}O_2$ may increase with successive sprints, the supply of ATP made by the aerobic system is significantly less than required for repeated sprints (Gaitanos et al., 1993) and uses a lower ATP turnover rate. As such, while this could guard against a build-up of fatiguing by-products (and sprint frequency/duration can be increased), it would not be able to sustain power output (i.e., sprint performance).

RSA is greater when tested in conditions of hyperoxia (Charles et al., 1996; Hogan et al., 1999) or enhanced oxygen availability (via erythropoietin injection) (Balsom et al., 1994a); the opposite is true when RSA is tested in hypoxic conditions (Balsom et al., 1994b). The consensus is that a greater quantity of PCr at the start of each sprint would reduce the demand on anaerobic glycolysis (and concomitant fatiguing by-products, e.g., H^+ and P_i) and enhance ATP turnover (Glaister et al., 2005). Glaister (2005) concludes that the key role of the aerobic system during repeated sprints is the return to homeostasis during rest. The natural assumption is that increasing $\dot{V}O_2$max will increase recovery rates and thus improve RSA. While there is little contention to this, it is worth noting that there is probably an optimal value above which further increases in RSA may not be noted (Bishop et al., 2011).

SECTION SUMMARY AND NON-CHEMICAL SOURCES OF FATIGUE

Sprint power is dictated by the amount and rate at which ATP is synthesised and then hydrolysed, and three mechanisms principally contribute to ensuring that ATP is resynthesised as fast as it is hydrolysed. These are (1) the donation of a phosphate group from PCr, (2) substrate level phosphorylation involving the breakdown of glycogen or glucose to pyruvate, and (3) oxidative phosphorylation. The rate of hydrolysis is based on the number of reactions required, while the ability to sustain ATP turnover at fast rates is based on PCr availability and avoiding metabolic by-product accumulation (e.g., Pi, H^+). As sprint frequency increases, and rest periods do not allow for sufficient recovery, ATP synthesis becomes progressively supported by oxidative phosphorylation. While oxidative phosphorylation allows for sustained work periods and repeated efforts, it does so with reduced metabolic power, and thus RSA declines.

It should also be noted that decline in RSA is related to additional muscular and neurochemical factors not outlined above. These include muscle excitability, whereby during intense contractions the Na^+ - K^+ pump cannot effectively reaccumulate the K^+ into the muscles cells, with the subsequent K^+ efflux causing muscle membrane depolarisation, and thus the reduction of muscle excitability (Clausen et al., 1998). There may be reductions to neural drive (i.e., a decrease in recruitment, firing rate, or both) and a reduced cerebral function owing to disturbances in neurotransmitter concentrations (e.g., serotonin, dopamine, acetylcholine) (Ross et al., 2001). There may be altered muscle recruitment strategies, such as timing delays between agonist and antagonist muscle activation – highlighting a possible decrease in muscle coactivation with fatigue (Hautier et al., 2000) – and a preferential recruitment of slow-twitch motor units (Matsuura et al., 2006). There may also be changes in stiffness regulation, with the negative effects of a more compliant system outlined in Chapter 3. Finally, fatigue is also likely to result from several homeostatic perturbations including hyperthermia, dehydration, and muscle damage.

TRAINING TO IMPROVE RSA

Having discussed the biochemical factors governing RSA, the aim of the following section is to outline how we can train to improve RSA via HIIT. As discussed, aerobic fitness is fundamental to RSA, and there is evidence HIIT may improve aerobic fitness to a greater extent than more traditional steady state endurance type training (Gormley et al., 2008; Esfarjani & Laursen, 2007; Helgerud et al., 2007; Wisloff et al., 2007) – this concept is discussed further in Chapter 5. We will start our introduction of HIIT approaches to improve RSA with those that may have their greatest benefit. Professor Ulrik Wisloff and colleagues are responsible for one such method, and have popularised the four-by-four running method that has proven popular and effective with soccer players and Nordic skiers, for example; this approach and its comparison to other methodologies is summarised in Table 6.1. Also, and as described by Baker (2011), aerobic fitness can be improved using 15s intervals at 100–120% maximal aerobic speed (MAS), with a 1:1 work to rest ratio (W:R) and continuing for five to ten minutes. Table 6.2 shows how to calculate interval distances from a 1.5 mile run, and how to organise these sessions within team sports. When estimating MAS, any distance (or time) can be used, but the athlete should be working for ≥ 5 minutes (Baker, 2011). When training for a sport like boxing, for example, it may be prudent to use these types of methods early on in the periodised plan (to ensure an appropriate aerobic base), before progressing the athletes towards shorter yet higher intensity intervals that are more relatable to the sport. In sports such as football, and particularly for midfielders where a high $\dot{V}O_2max$ may be just as important as RSA, it may be prudent to include these throughout the periodised plan.

Most RSA based studies use $\dot{V}O_2max$ as the major determinant of RSA performance – no surprise given its role in PCr resysnthesis and the contribution it makes as intervals extend. However, there are conflicting findings regarding this relationship that appear largely attributable to the RSA test used. For example, a moderate correlation (r = –0.35) between $\dot{V}O_2max$ and RSA was found when using 8 x 40m sprints with 30s of active recovery between sprints (Aziz et al., 2000), but not 6 x 20m sprints with 20s of recovery between sprints (Aziz et al., 2007). Bishop et al. (2004b) utilised an RSA involving 5 x 6s cycle sprints departing every 30s and found a relationship between RSA and $\dot{V}O_2max$ of r = 0.60. The discrepancies between these and others are probably attributable to the

length and frequency of the sprints used, as this is likely to alter the contribution of the aerobic system (Balsom et al., 1992). In essence, $\dot{V}O_2max$ has not been reported to relate to RSA when only a few sprints of less than 40m (or 6s) have been used (Da Silva et al., 2010). Also, in protocols using a W:R ≥ 1:5, there may be sufficient recovery provided for the aerobic system to resynthesise ATP and PCr despite inadequate fitness levels.

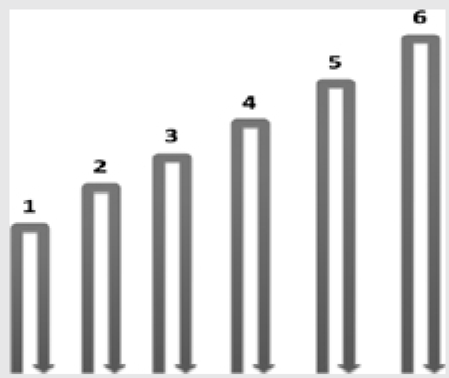
TABLE 6.1 Effective training systems to enhance aerobic fitness. Adapted from Helgerund et al. (2007).

Training group	*Protocol*	*Training intensity*	*Pre-training VO_2max*	*Post-training VO_2max*
Long slow distance running (LSD)	Continuous run at 70% HRmax for 45 min	Low–moderate	55.8 ± 6.6 (ml/kg/min)	56.8 ± 6.3 (ml/kg/min)
Lactate threshold running (LT)	Continuous run at lactate threshold (85% HRmax) for 24 min	Moderate–high	59.6 ± 7.6 (ml/kg/min)	60.8 ± 7.1 (ml/kg/min)
15/15 interval running	47 repetitions of 15s intervals at 90–95% HRmax with 15s of active resting periods at warm-up velocity, corresponding to 70% HRmax between	High	60.5 ± 5.4 (ml/kg/min)	64.4 ± 4.4 (ml/kg/min)*
4 x 4 min interval running	4 x 4 min interval training at 90–95% HRmax with 3 min of active resting periods at 70% HRmax between each interval	High	55.5 ± 7.4 (ml/kg/min)	60.4 ± 7.3 (ml/kg/min)*

Notes: * significantly ($P < 0.001$) different from pre- to post-training

TABLE 6.2 Interval distances for high-intensity interval training using MAS and calculated using a 1.5 mile run time of ten minutes. Adapted from (Baker, 2011)

Training protocol	• 15s intervals at 100–120% maximal aerobic speed (MAS) • Work to rest ratio of 1:1 • Repeat over 5 min using multiple sets as appropriate
Calculating 100% MAS	• v = d/t • Where v = velocity (m/s), d = distance (m) and t = time (s) • 1.5 miles = 2413m; 10 min = 600s • v = 2414/600 = 4m/s
Calculating interval distance	If an athlete runs 4m every second, then he/she will run 60m in

	15s (4 x 15).
Calculating 120% MAS	1.2 x 100% MAS value i.e., 4m/s x 1.2 = 4.8m/s
Notes on shuttles and variations using agility drills	A 30m shuttle, i.e., out and back covering 60m, probably represents 120% MAS as you must factor in the change of direction.
Don’t individualise too much	We don’t recommend calculating lane distance for everyone in the group. Instead, simply group runners based on 30s intervals.
What does it look like?	 For example, group 1: 12 min for 1.5 mile, therefore they run out and back 25m (≈120% MAS), up to group 6: 9.5 min/1.5 mile = 32m out and back.
What if you do not have the space?	Assuming only a 20m shuttle is available. Prior to the run (but within the 15s), athletes perform an exercise the intensity of which is dependent of how short the lane is. The exercise may be a series of tuck jumps or as simple as starting from a prone position.

Adaptations via $\dot{V}O_2$max may be largely determined by improvements in blood flow (i.e., central factors), via increased stroke volume, for example (Basset & Howley, 2000). Unsurprisingly, RSA has also been found to strongly correlate with peripheral factors (Spencer et al., 2005). For example, Da Silva et al. (2010) showed that an RSA test consisting of 7 x 35m sprints (involving a change of direction) and a between-sprint recovery period of 25s produced high values of lactate (15.4 ± 2.2 mmol/L). Logically then, Da Silva et al. (2010) found that the velocity at the onset of blood lactate accumulation (vOBLA) better correlated with RSA performance (r = –0.49); vOBLA reflects peripheral training adaptations such as increased capillary density and capacity to transport lactate and H^+

(Billat et al., 2003; Thomas et al., 2004). Therefore, to improve RSA, it appears prudent to not only target the development of vOBLA, but also the muscles' buffer capacity. Several intervals of 30–60s, with 1:1 W:R may therefore be beneficial. Also, to enable the accumulation of H^+, passive recovery between intervals may be best.

Finally, Da Silva et al. (2010) (protocol aforementioned) and Pyne et al. (2008) (using 6 x 30m sprints with 20s of rest) found that the strongest predictor of RSA was actually anaerobic power, i.e., the fastest individual sprint time; this explained 78% of the variance and had a relationship (*r*) of 0.66, respectively. Results suggest that in addition to training targeting the improvement of $\dot{V}O_2max$, vOBLA, and muscle buffer capacity, some training should also focus on improving strength, power, and sprint speed (including acceleration). As well as traditional gym and track-based sessions (outlined in Chapters 15, 16 and 18, respectively), this may also need to include single repetition, all-out 30s intervals to maximally activate glycolytic flux and thus adaptations in in PFK and phosphorylase. The former adaptations may be on account of increases in rate of force development, stretch-shortening cycle mechanics, movement efficiency, and also increases in Type II muscle fibre content. These fibres, which contain higher amounts of PCr than Type I (Sant'Ana Pereira et al., 1996), may be able to replenish ATP faster. However, this advantage may diminish after several sprints as Type I fibres have better mitochondrial density and thus are better able to resynthesise PCr. Furthermore, and as an additional caveat to this, enhanced initial sprint performance via improved glycolytic flux may actually lead to increased fatigue in subsequent sprints given the likely build up of additional fatiguing by-products. So this training intervention may need to be supported by others aimed at increasing $\dot{V}O_2max$ and buffer capacity to truly to see it as a positive adaptation. Training approaches associated with each energy system are identified in Table 6.3.

REPORTING RESULTS FROM RSA TESTS

It is important to judge the efficacy of any training intervention, and this can be done by monitoring an athlete's RSA performance over time. Once a drill has been designed that replicates the sport and, importantly, requires

athletes to work at an intensity that represents (and even surpasses) a worst-case scenario bout of play, there are considerations with regards to data analysis. The method of data analysis for RSA testing is largely a question of two alternatives: (1) reporting total (or mean) sprint time for all sprints, or (2) the rate of fatigue (or performance drop-off). The latter can be reported by one of two methods: (1) sprint decrement (Sdec) or (2) the fatigue index (FI). The formula for each, according to Spencer et al. (2005) is listed below in Equations 6.4 and 6.5, respectively. Unlike the FI, the Sdec takes into account all sprints and is less influenced by a good or bad start or finish (Bishop et al., 2001).

TABLE 6.3 High-intensity interval training based on each energy system

Training focus	*Training plan*	*Rationale*
Phosphocreatine system	Gym based strength and power Track based max speed and acceleration Repeated bouts (6–12) of 6–30s, with ~ 60s rest ≥ 2 min intervals, separated by relatively shorter rest periods e.g., 1 min, and ≥ 4 reps	Increase initial sprint speed May increase PCr stores by virtue of increased Type II fiber concentration Reduced effort through increases in strength, power (including RFD and SSC mechanics), and technical proficiency Increases in aerobic capacity and thus creatine shuttle efficiency
Anaerobic glycolysis	Maximal intensity 30s intervals separated by > 4 min to ensure subsequent intervals are again maximally utilizing anaerobic glycolytic enzymes	Maximally activate and thus adapt key enzymes, e.g., PFK and phosphorylase
Muscle buffer capacity	Repeated bouts (~ 6) of 30–60s intervals, with work to rest ratio of 1:1. Utilise a passive recovery	Increase and accumulation of H^+ and thus buffer capacity
Aerobic system	Longer duration (≥ 2-min) intervals (at ~ VO_2 max) separated by relatively shorter rest periods, and ≥ 4-reps	Improve PCr resynthesis via the creatine shuttle, mitochondrial biogenesis, and enhanced blood flow.

Equation 6.4

Calculation of sprint decrement (S_{dec})

S_{dec} (%) = [(S1 + S2 + S3 + …+ S_{final})/S1 X number of sprints] –1 X 100

Equation 6.5

Calculation of fatigue index (FI)

FI (%) = [($S_{slowest}$ – $S_{fastest}$)/$S_{fastest}$] X 100

To improve reliability, Spencer et al. (2005) advise that 5 minutes prior to testing, athletes complete a single criterion sprint. During the subsequent first sprint of the RSA test, athletes must achieve at least 95% of this score. Should they fail, the test is terminated and restarted following another 5 minute break. While total (or mean) sprint time demonstrates good reliability (CV < 3%), indices of fatigue are much less reliable (CVs 11–50%); therefore we advise the former be predominately used (Oliver, 2009; Spencer et al., 2006).

CONCLUSION

It is the manipulation of exercise duration, frequency, and rest period that brings about specific adaptations to metabolic pathways. The results of Balsom et al. (1994b) provide a useful summary of this point. They found that 40 x 15m sprints (~ 2.5s), with 30s rest could be completed without any reduction in performance. However, using the same rest period, 40 x 30m (~ 4.5s) and 15 x 40m (~ 6s) sprint times increased significantly, and after only the third 40m sprint, times were already significantly longer. Blood lactate was also only elevated in the longer sprints. Although all sprint combinations were matched for distance (i.e., each covered 600m), each emphasised a different energy system, with the final one presumably incorporating the largest aerobic stimulus. Such (small) differences in HIIT design can make all the difference to competition performance. Therefore, when programming, S&C coaches need an understanding of exercise biochemistry to ensure they are targeting the appropriate energy system.

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CHAPTER 7

Concurrent training

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INTRODUCTION

Successful sports performance is multifaceted and includes optimal preparation of skill, tactics, and physical qualities. Sports such as marathon running and weightlifting have clear physical qualities. For example, a marathon runner requires excellent aerobic capacity with elite athletes typically demonstrating $\dot{V}O_2$ max values of 70–85 ml kg^{-1} min^{-1} (Joyner & Coyle, 2008). In contrast, weightlifting necessitates high levels of muscular force, and as a result, a greater cross-sectional area (CSA) of type II muscle fibers (Aagaard et al., 2011; Fry et al., 2006). Therefore, the amount of time dedicated to enhancing strength and power qualities by the endurance athlete is markedly lower than that dedicated by the weightlifter, just as the time dedicated to aerobic qualities is lower for the weightlifter compared to the marathon runner.

There are many sports that require a range of physical qualities including both strength and aerobic capacity for optimal performance. For instance, in a single rugby union match it may be necessary for a player to accelerate past their opponent in a line break (acceleration and power), ruck and maul in offensive and defensive plays (muscular size and strength), and cover great distances, tracking and tackling throughout (aerobic capacity). Therefore, training for rugby and many other team sports requires multiple physical qualities, which often need to be developed concurrently (Chiwaridzo et al., 2016). Typically, these qualities are classified into two

training categories, endurance and strength training. Endurance training is commonly denoted by relatively low intensity and relatively high volume training which places greatest demand on oxidative metabolism, and promotes adaptations specific to enhanced oxygen uptake and delivery, such as increased mitochondrial and capillary density (Baar, 2014) (see Chapter 5). In contrast, strength training is characterised as high intensity and low volume, and places greater demand on anaerobic metabolism and promotes adaptations enhancing muscle CSA and neuromuscular efficiency to enhance force production (Farup et al., 2012) (see Chapter 2). Herein lies the concern, as concurrent strength and endurance training promotes diverse physiological adaptations (Nader, 2006), it is important that strength and conditioning coaches and sport scientists have appropriate physiological knowledge to optimise programming and thus training adaptations. The aim of this chapter, therefore, is to discuss the adaptive response to concurrent exercise, and identify how periodisation can minimise the interference effect of these diverse adaptations.

THE INTERFERENCE EFFECT

The interference effect is possibly due to the high volume and long duration that is often associated with endurance based training (Wilson et al., 2012). It is presumed that endurance exercise interferes with resistance exercise sessions via residual fatigue and substrate depletion, and therefore blunts any muscular development (Leveritt & Abernethy, 1999). This is examined more precisely over the following sections.

Neural development

It has been well documented that increases in maximal strength during the initial weeks of strength training can be attributed largely to the increased motor unit activation of the trained agonist muscles (Häkkinen et al., 1998; Häkkinen et al., 2001a; Häkkinen et al., 2001b). It has been demonstrated that strength training, performed concurrently with endurance training, has no detriment to neuromuscular characteristics in trained populations (Mikkola et al., 2007; Paavolainen et al., 1999; Støren et al, 2008; Taipale et al., 2010). Häkkinen et al., (2003) demonstrated that alongside large gains

in maximal force there was an increase in the maximum integrated electromyograms (EMGs) in the leg extensor muscles during a concurrent training programme lasting 21 weeks. Increases in EMG amplitudes via strength training would result from the increased number of active motor units and/or an increase in their rate coding (Sale, 1992). More recently, Jones et al., (2013) reported no differences in neuromuscular responses between strength training and concurrent training interventions, which is in agreement with previous research stating neuromuscular characteristics are not fully inhibited by concurrent training (McCarthy et al., 1995; Mikkola et al., 2007; Paavolainen et al., 1999). However, where an interference effect has been demonstrated, it is purported to manifest as 1) alteration in the neural recruitment patterns of skeletal muscle (Chromiak & Mulvaney, 1990; Gergley, 2009), 2) limitation in force generation (Rhea et al., 2008; Rønnestad et al., 2012), and 3) increased neuromuscular fatigue from increased training demands of high volume endurance training (Leveritt & Abernethy, 1999; Davis et al., 2008). These findings have been supported via a meta-analysis that indicated whilst muscular power increased, the magnitude of change was significantly lower in concurrent trained groups (ES = 0.55) compared to strength-only trained groups (ES = 0.91) (Wilson et al., 2012). It is speculated that forces at high contraction velocities, i.e., movements that need 'explosive' strength with high levels of rate of force development (RFD), are affected more by endurance training than force at low fascicle shortening velocities (Dudley & Djamil, 1985).

Muscular development

Following periods of concurrent training, skeletal muscle CSA has been found to be depressed (Bell et al., 1991), and within the total CSA, individual muscle fibers have hypertrophied to a lesser degree (Kraemer et al., 1995; Bell et al., 2000). Mikkola et al., (2012) postulate that during bouts of concurrent training, optimal adaptation of trained muscles to both strength and endurance training stimuli may not be morphologically or metabolically possible. Possibly elevations in the catabolic hormonal state of skeletal muscle could lead to a reduced change in the CSA (Kraemer et al., 1995; Bell et al., 2000). In support, there is a likely impact of testosterone and cortisol interference due to mixed endocrinal responses to training (Taipale & Häkkinen, 2013). Also, endurance training may

decrease muscle fiber size in order to accommodate increases in capillary and mitochondrial density (Sale et al., 1990). This may be partly due to the oxidative stress imposed on the muscle and the need to optimise the kinetics of oxygen transfer because of the addition of endurance training to strength training (Häkkinen et al., 2003). Furthermore, a lack of development in muscle CSA during concurrent training could be attributed to chronic muscle glycogen depletion (down regulating the signaling cascade required for protein accretion, as well as reducing training performance) and an increase in catabolic hormones (Mikkola et al., 2012). Further analysis demonstrates that potential disruptions to muscle hypertrophy during concurrent training are more prominent when strength training is concurrently performed with running compared to cycling (Wilson et al., 2012). This is potentially due to greater levels of muscle damage in running, thereby reducing the development of muscle tissue via competing demands for tissue regeneration via the inflammatory process (Clarkson & Hubal, 2002).

Molecular signaling

Excessive bouts of endurance exercise are known to reduce rates of protein synthesis for several hours following the cessation of training (Rennie & Tipton, 2000). Molecular signaling research has evidenced that during (and following) endurance training the metabolic signaling pathways that are linked to substrate depletion and calcium release and uptake into the sarcoplasmic reticulum are activated (Coffey & Hawley, 2007). The secondary messenger adenosine monophosphate-activated kinase (AMPK) is activated, as its role is to increase mitochondrial function to enhance aerobic capacity (Rose & Hargreaves, 2003). However, this activation inhibits the mammalian target of rapamycin (mTOR), whose role is to mediate skeletal muscle hypertrophy through upregulation of protein synthesis via activation of ribosome proteins (Bodine, 2006). Knowledge of this signaling system informs us that in conditions of low glycogen and high concentration of calcium and AMP (as would occur during aerobic training), the AMPK pathway is activated and thus protein accretion (via the mTOR pathway) is significantly reduced. Thus, strength training in a fasted or fatigued state may not be best practice.

Cardio-respiratory development

There is empirical evidence that in elite endurance athletes, strength training can lead to enhanced long-term (> 30 min) and short-term (< 15 min) endurance capacity (Aagaard & Andersen, 2010). Investigations into adaptations of cardiorespiratory function have indicated that there are no differences in the magnitude of adaptation when endurance training is completed in isolation or concurrently with strength training (Bell et al., 2000; McCarthy et al., 2002). The greatest impact on cardiorespiratory adaptations come when the peripheral adaptations (e.g., capillary and mitochondrial density) are blunted when the demands of resistance training increase the competition for rises in contractile protein synthesis (promoting an increase in fibre size and muscle CSA) and an increase in glycolytic enzymes (Docherty & Sporer, 2000). More recent focus on cardiorespiratory adaptations has investigated the acute effects of concurrent training on oxidative metabolism (Alves et al., 2012; Kang et al., 2009). Alves et al., (2012) did not observe differences in mean values of VO_2 or HR during endurance exercise performed prior to or following a strength training session. However, Kang et al., (2009) demonstrated greater mean values for participants' VO_2 when endurance exercise was performed following strength training compared with endurance exercise only. There are a number of methodological variations that can explain these differences, i.e., intensity of endurance exercise, strength exercises chosen, and populations used.

The positive effects of strength training for endurance athletes may occur independently to changes in cardiorespiratory development (Paavolainen et al., 1999) and could be due to improvements in RFD that aide improvements in exercise economy. Further, improved RFD may reduce time to reach the desired force for each movement via reduced ground contact times. A shorter contraction time coupled with relative high force production would also be likely to enhance the utilisation of elastic energy in the muscle-tendon system in the lower body (as long as impulse is maintained), and could reduce the demand of ATP production, thus improving exercise economy.

TRAINING STRATEGIES TO MINIMISE INTERFERENCE

Training periodisation

When periodising a training programme for a sport that includes a range of physical qualities, planning of training units within a training day, microcycle, and mesocycle needs to be cautiously managed to minimise the interference effect; one training session may inhibit adaptations to a prior or subsequent training unit. In addition, the inclusion of training units such as technical and tactical skills within the sport may provide enough stimuli to maintain or enhance physical qualities and such training stressors should be considered in the periodised plan to optimise fitness and minimise fatigue (Issurin, 2010; Suarez-Arrones et al., 2014).

An eight-week preseason concurrent strength and aerobic training programme (prioritising 1RM half back squat and Yo-Yo Intermittent Recovery Test) was effective at improving both cardiovascular and neuromuscular measures in professional soccer players (Wong et al., 2010). The experimental group completed twice weekly strength training units and eight minutes of high intensity running sessions (low volume) on the same day, additional to their normal 6–8 weekly soccer training units. Likewise, Sedano et al., (2013) demonstrated improved running economy, 3 km time trial and 1RM strength with concurrent training in elite endurance athletes. Here participants completed their normal 6 weekly endurance units (intervals x 3, moderate running 0.5–1.5 h x 2 and fast running 0.5–1 h x 1) with the inclusion of two weekly strength units over a 12-week training programme. Noticeably, both studies included two daily training units when resistance training was performed; during these days, resistance training units were performed in the morning prior to endurance units performed in the afternoon. Piacentini et al., (2013) also demonstrated similar results with concurrent training in highly trained master endurance athletes. These studies used linear periodisation patterns of increased intensity over time and demonstrated improvements in strength and endurance performance measures with no hypertrophy or concomitant changes to anthropometry. While these concurrent training studies demonstrate minimal interference effect to cardiovascular performance in aerobic endurance based sports, they conversely demonstrate endurance training may inhibit strength training adaptations such as muscle CSA to a greater degree. Therefore, consideration and appropriate planning must be applied when planning

training blocks to stimulate muscle hypertrophy for collision sports where a goal of training is likely to be an increase in muscle mass.

Comparing athletes with low resistance training age to well-trained strength athletes is unwise as the stimulus for adaptation is different. Longitudinal research where strength based athletes have participated in concurrent training (Appleby et al., 2012; Stodden & Galitski, 2010) have typically dedicated specific training periods such as preseason (Appleby et al., 2012) or off-season (Stodden & Galitski, 2010) to hypertrophy development and included a minimum of three resistance training sessions per week for this mesocycle. This form of periodisation enables a large training stimulus to be applied to well-trained athletes. During in-season, training frequency was reduced to a minimum of one session a week to maintain physiological adaptations made in pre- and off-season. In both these studies, 1RM strength improved within year one and year two, alongside the inclusion of speed, agility, aerobic capacity, technical and tactical training units. A review on the development, retention, and decay of strength in strength and power based athletes confirm these programming variables, suggesting that to maintain strength, 1–2 training units per week are required (McMaster et al., 2013). Interestingly, it also speculated that a detraining period of three weeks has no effect on muscular strength (McMaster et al., 2013). This provides valuable information in regards to the duration of strength training residuals and subsequent opportunities for tapering strategies or prioritising other training units.

For successful periodisation within sports where concurrent training is required, it would be prudent to determine off-season and in-season periods to establish specific training goals. Furthermore, determining preseason and in-season mesocycle goals would help focus programming and lessen the interference effect of physiological adaptations of diverse physical qualities. For example, García-Pallarés et al., (2009) demonstrated in elite kayakers that strength and endurance qualities can be trained concurrently with positive performance outcomes. The distinctive aspect of this research was coupling hypertrophy training with aerobic training in the first mesocyle, and strength training and maximal aerobic power in the second mesocycle. The rationale for this was due to the physiological adaptations expected, hypertrophy (increase in contractile proteins synthesis) and aerobic power training (increase in oxidative capacity) promote opposing adaptations at a peripheral level (García-Pallarés et al., 2009). Periodising fitness qualities

in this manner has the potential to limit the interference effect based on specific physiological adaptations. The use of transition or detraining periods from strength training units within programming may also be beneficial as 1) this period may enable restoration and supercompensation and 2) another training unit may be prioritised without detrimental effects to strength (McMaster et al., 2013; Sedano et al., 2013). Finally, special attention should be considered in regards to the type of sport, for example, contact sports may necessitate a need for hypertrophy and an increased frequency of resistance training units whilst minimising the amount of aerobic training units completed.

Training session sequencing

One opportunity to manipulate training variables and reduce interference may be through the sequencing of training units within a microcycle. In programmes that include both strength and endurance based training stimuli on the same day, the training outcome may be different depending on the session sequencing and the subsequent accumulated fatigue (as mentioned in the molecular signaling section). Some studies have investigated the endocrine response to training sequencing as chronic physical adaptations are enhanced by optimal endocrine responses (Craig et al., 1991; Kraemer & Ratamess, 2005). However, these investigations have continually provided mixed conclusions. Cadore et al., (2012) reported strength training after endurance training resulted in increased testosterone levels compared to strength training prior to endurance. In addition, no change in cortisol response was reported, regardless of exercise sequencing. Goto et al., (2005) support endurance-strength training, as they found no difference in testosterone or cortisol concentration after resistance only or endurance-strength sequencing. Moreover, Taipale & Häkkinen (2013) reported a reduction in testosterone (at 24 and 48hrs recovery) during strength-endurance sequencing alongside lower levels of cortisol post training compared to the endurance-strength sequencing group. Utilising endurance-strength sequencing may also allow for the strength training stimulus to be the last stimulus of the day (evening session) where strength levels are at their highest (Souissi et al., 2013). This sequencing may result in an elevation in the mTOR signaling pathway and maximise post-session recovery time, facilitating more time for protein synthesis and a more

favorable anabolic environment (Lundberg et al., 2012; Chtourou et al., 2014), including while sleeping. Equally, it has been reported that strength training in the morning produces a ‘priming effect’ resulting in improved physical performance six hours later (Cook et al., 2014). (See Chapter 10 for additional detail regarding priming strategies.) Although this phenomenon has not been studied in regard to training session adaptations or to the adaptation and signaling interaction, it may be that there is still much more to learn.

Further studies have also measured performance related outcomes, such as Collins & Snow (1993) and Chtara et al., (2008) who report training sequence has no significant effect on maximal strength or aerobic power adaptations in untrained men. Conversely, well-trained kayakers did not show improvement in a maximal strength mesocycle when strength training was performed prior to endurance training or with at least six hours of rest (García-Pallarés et al., 2009). However, as discussed later, it is important to consider all training variables such as volume and intensity when comparing magnitude of change after training interventions.

This supports the requirement for a strong consideration of the training variables, not just the overall sequence when programming concurrent training, especially when endurance training is to be performed prior to strength training. Therefore, the mixed conclusions in the literature of the optimum exercise sequencing may be due to variation in other variables, such as the training duration, intensity, and modality (Kraemer et al., 1995; Rønnestad et al., 2012; Bell et al., 2000). Supporting this, Wilson et al., (2012) reported that endurance training modality and volume (frequency and duration) are key determining factors of the interference effect. Therefore, sequencing studies may only be compared if these variables have been matched in the studies protocols.

Training recovery

Insufficient recovery between training sessions may limit the desired adaptations from previous training, cumulatively contributing to overtraining syndrome. Residual fatigue from aerobic training may reduce the quality of strength training sessions by alterations in the neural recruitment patterns of skeletal muscle (Chromiak & Mulvaney, 1990; Gergley, 2009), limitations to adequate force generation (Rhea et al., 2008;

Rønnestad et al., 2012), and increased neuromuscular fatigue (Leveritt & Abernethy, 1999; Davis et al., 2008). For example, Schumann et al., (2013) reported that endurance – strength training sequencing resulted in longer lasting fatigue levels post training session (creatine kinase, testosterone cortisol ratio, and maximal force production) compared to the strength – endurance sequencing group. Robineau et al., (2016) concluded that strength and power adaptations were inhibited unless at least six hours recovery was allowed between training sessions (strength followed by high intensity endurance exercise); however, a 24-hour recovery period was superior to further reduce interference. Furthermore, Sale et al., (1990) reported that strength and endurance training performed on the same day (alternating order) had no effect on muscle hypertrophy, but did cause a significant reduction in strength development in untrained men compared to separate day training (~ 24 hours rest). It is likely that the reduced interference with increasing recovery between sessions is due to the lower likelihood of an interference effect in the muscle signaling pathways (Lundberg et al., 2012), a maximised recovery time allowing for increased protein synthesis, and management of fatigue before the following training sessions (Chtourou et al., 2014).

Interference may also be increased when the same muscle groups are utilised for strength and endurance based training (Craig et al., 1991; Sporer & Wenger, 2003). Sporer & Wenger (2003) report that lower body strength was significantly decreased for at least eight hours after completion of both a sub-maximal aerobic training protocol (36 min cycling at 70% maximal power at VO_2) and a high-intensity interval training protocol (three min. work and three min rest at 95–100% of maximal power at VO_2) with no difference between groups at any recovery time point. Moreover, strength and endurance training performed on different days resulted in a greater hypertrophy effect size (although not significantly different) than those performed on the same day (1.06 vs. 0.8) (Wilson et al., 2012). Where this is not possible, athletes who engage in multiple strength training units per week may benefit from utilising a split training routine where upper body strength training can be completed on days that contain aerobic training sessions (given these predominately tax the legs), as upper body hypertrophy has shown to have less interference during periods of concurrent training compared to lower body hypertrophy (Wilson et al., 2012).

Training intensity

It may also be important to consider endurance training intensity as Chtara et al., (2008) and Davis et al., (2008) reported that interference is more likely to occur at aerobic training intensities close to maximal oxygen uptake. In addition, it may also be recommended that long duration aerobic exercise should be avoided as the depletion of glycogen stores negatively affects subsequent training sessions (Bergström et al., 1967). However, Sporer & Wenger, (2003) concluded that endurance training intensity had no significant acute effect on strength after eight hours rest. Furthermore, De Souza et al., (2007) compared the acute effect (ten minutes rest) of two endurance training protocols (one close to the second ventilatory threshold and the other of a higher intensity at maximal aerobic speed) on maximal strength. Results demonstrated that neither endurance protocol had a detrimental effect on maximal strength. Silva et al., (2012) support this by reporting no difference in strength improvements after continuous low intensity or intermittent high intensity aerobic training when performed prior to strength training over an eleven week period. Interestingly, it has also been reported that high intensity aerobic training may minimise the interference effect due to the recruitment of high threshold motor units and muscle fibers and a potential reduction in training volume. For example, Wong et al., (2010) reported significant improvements in strength, sprint speed, and aerobic performance after strength sessions were utilised concurrently with high intensity aerobic training (15:15s at 120% maximal aerobic speed and passive recovery). Importantly, this training allowed for ~ 5 hours between the morning strength session and the afternoon high intensity aerobic session, which may have also contributed to the significant adaptations found. High intensity interval training is discussed further in Chapter 6.

Training frequency and volume and mode

Optimal training frequency is also important as a number of studies investigating concurrent training have reported varied conclusions on whether endurance training attenuates strength and power adaptations (Sale et al., 1990; Craig et al., 1991; Abernethy & Quigley, 1993; Hennessy & Watson, 1994; Kraemer et al., 1995; McCarthy et al., 1995). Jones et al.,

(2013) speculated that these differences may be linked to endurance training frequency, as attenuated responses are more often reported in studies utilising a high (Craig et al., 1991; Hennessy & Watson, 1994; Kraemer et al., 1995) vs. a low training frequency (Abernethy & Quigley, 1993; McCarthy et al., 1995; Sale et al., 1990). Jones et al., (2013) reported that recreationally trained men taking part in a high frequency strength and muscular endurance training (both 3 x per week) resulted in lower strength and hypertrophy adaptation compared to a programme performing strength only (3 x per week) or low frequency strength and muscular endurance training (3 x strength and 1 x endurance per week). In contrast, McCarthy et al., (1995) found similar improvements in maximal strength and power when combined strength and endurance training was performed three days per week compared to strength training only. These differences may be due to the competing peripheral demands of the isokinetic knee extension endurance training performed in the study by Jones et al., (2013) compared to the central demands of a 50-min cycle at 70% heart rate reserve reported by McCarthy et al., (1995). Subsequently, it may be important to think about the peripheral demands, potential muscle damage, and biomechanical similarity of the endurance training intervention when minimising the interference effect. Wilson et al., (2012) support this, reporting smaller reductions in lower body hypertrophy, strength, and power, when endurance exercise was performed on a cycle ergometer compared to running.

It should be noted that methodological differences make comparing and contrasting frequency research problematic due to variations in training duration and intensity, thus producing erroneous results due to differences in total training volume. Supporting this, through a meta-analysis of concurrent training studies, Wilson et al., (2012) concluded that there is a significant relationship between endurance training frequency, duration, and lower body adaptations in hypertrophy (r = –0.26 and –0.75, respectively), strength (r = –0.31 and –0.34, respectively), and power (r = –0.35 and –0.29, respectively). However, no correlation between endurance training intensity and effect sizes was reported due to insufficient data. The prescription of strength training should also be monitored, as when concurrent training is necessary, the overall training load is likely much higher due to needing to meet this minimum-dose response of two different fitness qualities. Therefore, strength-training regimes of moderate volume

may be a sufficient and a safe alternative to high volume training to failure (García-Pallarés et al., 2009; Izquierdo-Gabarren et al., 2010).

SUMMARY

The concurrent training research provides equivocal findings on rate and magnitudes of adaptations (positive and negative in their manifestation) across a number of physiological variables including strength, power, and cardiorespiratory functions. This wide range of findings may be due to the large number of variables contributing to the potential interference effect. The research seems to support that the interference effect has its greatest effect on strength development (via hypertrophic adaptations) and that the most likely mechanism of this interference is linked to the molecular signaling activated from the type of training undertaken. Athletes who require high levels of muscular strength and hypertrophy may therefore be best limiting any long periods of concurrent training.

During the planning of training, overall periodisation including microcycles and mesocycles need to be cautiously managed to control fatigue and minimise the interference effect (see Figure 7.1 for recommendations). It would be prudent to determine off-season and in-season periods to establish specific training goals where as much focus can be placed on a single training outcome as possible. It may also be optimum to reduce the frequency of endurance training (and strongly consider total accumulated fatigue) when hypertrophy adaptations are required. During training cycles where concurrent training is unavoidable, it would be prudent to consider the level of stimulus required of different modes of training and determine a minimal dose response. For example, detraining or transition periods from strength training may be beneficial to allow supercompensation and for other physical qualities, such as speed and agility, to be prioritised.

It may be concluded that best practice is to have strength and endurance training units split by at least 24 hours of rest; where this is not possible, 6–8 hours would be sufficient. In scenarios where training density must be much higher, strength training should follow endurance training to ensure optimal strength improvements, but the overall accumulated fatigue being carried from one session to another should be the main variable of interest. This may also be managed via a reduced endurance training frequency of

less than three sessions per week. In addition, aerobic training using different muscle groups should be considered. For example, where 24 hours of rest cannot utilised, upper body strength development may best be performed on aerobic training days. Aerobic training may also be completed via a mode that does not interfere with areas of desired strength development or reduces the level of eccentric stress, for example, an arm or cycle ergometer compared to running. Also appropriate fueling, i.e., glycogen replenishment prior to strength training, would be beneficial.

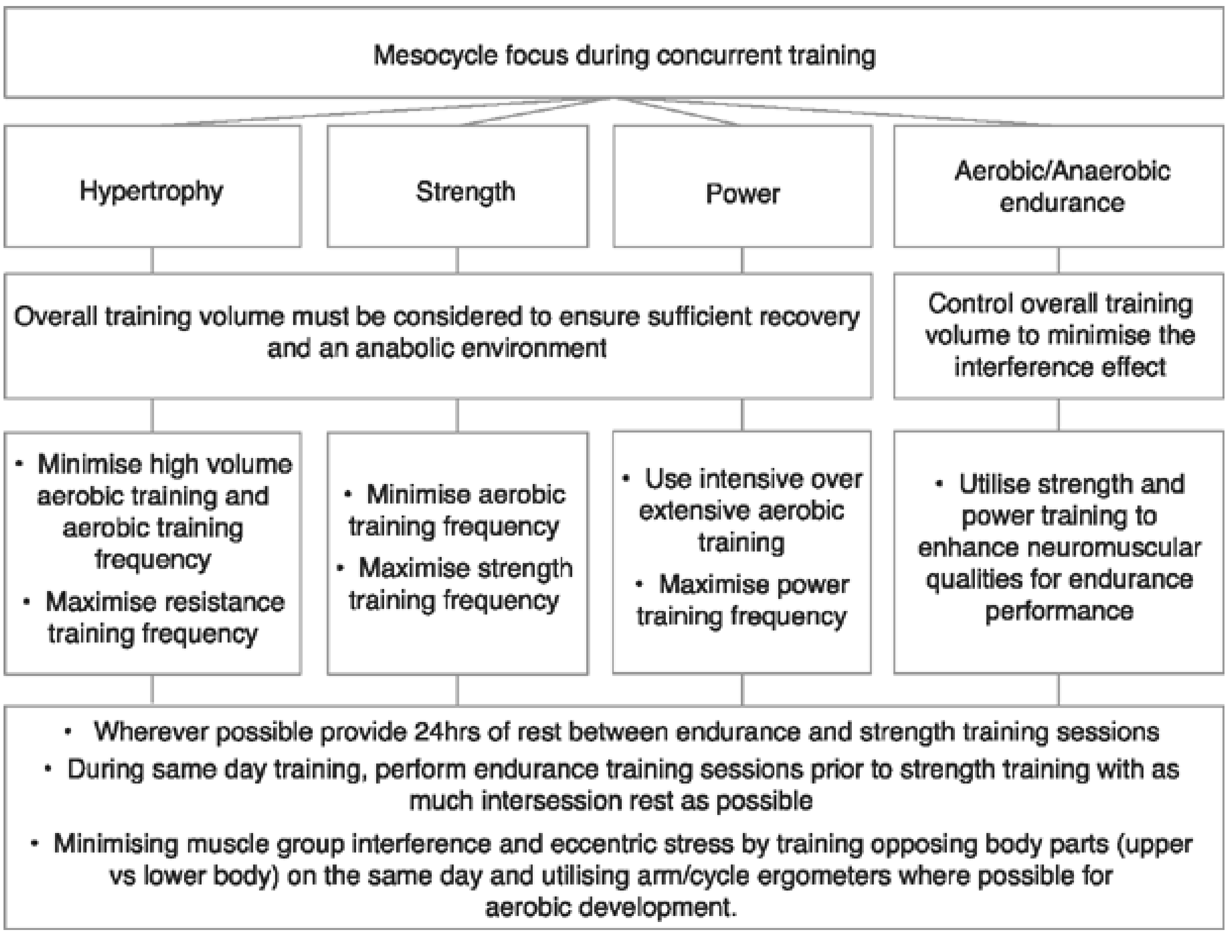

FIGURE 7.1 The recommended decision making process during periods of concurrent training.

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PART 2

Programming and monitoring for your athlete

CHAPTER 8

Periodisation

Anthony Turner and Paul Comfort

INTRODUCTION

Periodisation (also referred to as phase potentiation) is regarded as a superior method for developing an athlete's performance (Fleck, 1999; Haff, 2004a; Haff, 2004b; Stone et al., 1999a; Stone et al., 1999b; Stone et al., 2000). However, because peak performance can only be maintained for two to three weeks (Stone, Stone, & Sands, 2007), the ability to phase training appropriately to ensure that the athlete's peak level of performance coincides with a competition date long into the future (e.g., the Olympics, or key matches in team sports) is a fundamental skill to all strength and conditioning (S&C) coaches. Such levels of performance may only be attained following the appropriate application of periodisation, whereby a calculated manipulation of training parameters (e.g., frequency, intensity, duration, volume, exercise selection) ensures optimal adaptations and minimal fatigue at the point of competition. Despite an apparent lack of scientific rigour to govern its application (Cissik, Hedrick, & Barnes, 2008; Fleck, 1999; Fry, Morton, & Kreast, 1992; Plisk & Stone, 2003; Stone et al., 1999a), periodisation is widely practised (Durell, Puyol, & Barnes, 2003; Ebben & Blackard, 2001; Ebben, Carroll, & Simenz, 2004; Simenz, Dugan, & Ebben, 2005) and recommended (Haff, 2004a; Haff, 2004b; Plisk & Stone, 2003). The aim of this chapter is to provide the S&C coach with a

detailed overview of periodisation so as they may be cognizant of its theory and methodology. It is hoped that this will further facilitate its implementation and successful application.

DEFINING PERIODISATION

Periodisation may be defined as a training plan whereby peak performance is brought about through the potentiation of biomotors and the management of fatigue and accommodation. This is principally achieved through the logical yet creative variation of training methods, intensities and volume loads. Important to the latter, volume and intensity (volume load) share an inverse relationship (Figure 8.1) with the only notable exceptions being during periods of planned overreaching (discussed later). More recent research has identified that manipulating training load via cluster sets (Tufano et al., 2016) and higher volume (sets) powerlifting protocols (Schoenfeld, Ratamess, Peterson, Contreras, Sonmez, & Alvar, 2014) may also permit higher volumes of training at higher intensities. However, careful implementation of such strategies should be considered, preferably away from competition, to ensure that the higher training volumes do not negatively impact performance due to the associated increase in fatigue.

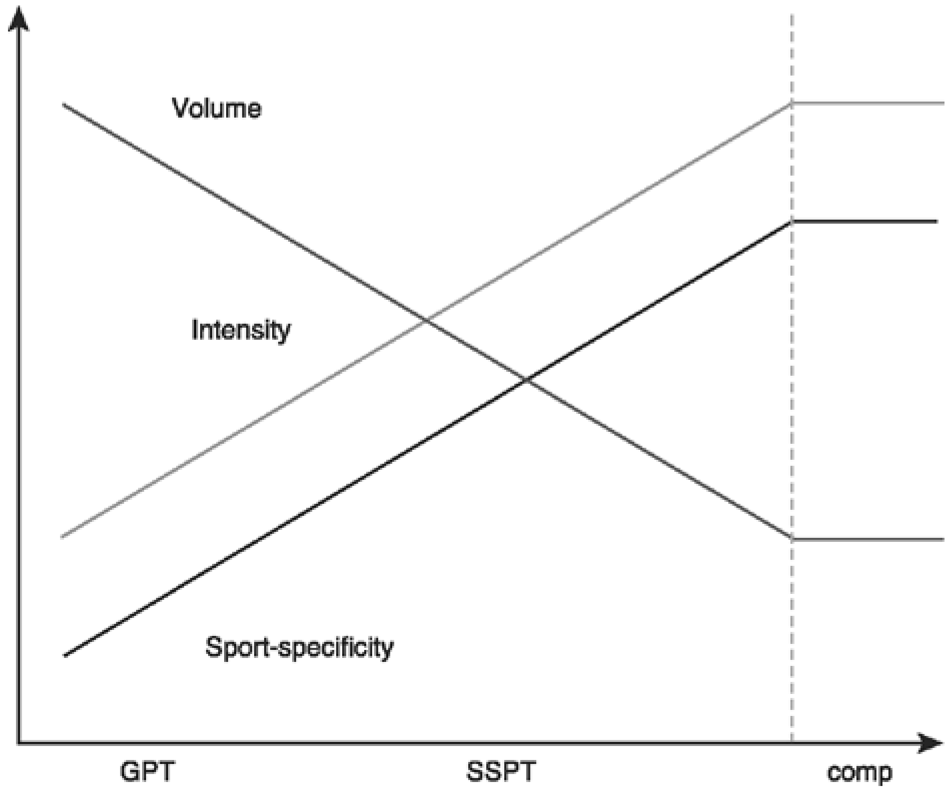

FIGURE 8.1 The inverse relationship between volume and intensity. In general, as the periodised programme advances and competition nears, intensity increases whilst volume decreases. GPT = general physical training; SSPT = sport-specific physical training; comp = competition.

Plisk and Stone (2003) suggest that periodisation should be applied on a cyclic or periodic basis, structured into macro-, meso- and microcycles that progress from extensive to intensive workloads. These cycles are often defined by their allotted period of time, with a macrocyle typically referring to a year, a mesocyle (each period/phase of focussed training) two to eight weeks, dependent on the competition schedule, and a microcycle one day to one week. There is, however, large variability in the time course of each with, for example, macrocyles running four years in the case of Olympic training programmes (quadrennial plan). Also, mesocycles are often divided into 4 ± 2 week blocks as this appears to provide the optimal time frame for adaptation in well-trained athletes (Matveyev, 1977; Plisk & Stone, 2003; Stone, Stone, & Sands, 2007; Zatsiorsky & Kraemer, 2006).

Periodisation is also often defined by its progression from general to special tasks (see Figure 8.1) whereby there is a conscious incorporation of technique/sport-specific biomotors as the programme progresses and

competition nears. It is important to note that, in terms of sport-specificity, this refers to training, which results in adaptations that achieve specific, pre-established goals, and not mimicking the movements of sporting tasks. Bompa and Haff (2009) also report two major phases of periodisation; the preparatory phase and the competitive phase. In addition, the preparatory phase has two sub-phases: general physical training (GPT) and sport-specific physical training (SSPT) (Table 8.1). The objective of the GPT is to improve the athlete's work capacity and maximise adaptations in preparation for future workloads. The SSPT serves as a transition into the competitive phase, whereby physical capacity is developed specific to the physiological profile of the sport, and where sportspecific biomotors are perfected. During the competitive phase, the work capacity developed during the SSPT should be maintained as a minimum objective. However, in team sports with regular competition and extended competition phases, mesocycles may be attributed to maintenance of some attributes and development of others. This phased approach is also essential to ensure that the desired muscular adaptations occur, as strength and power training result in different architectural adaptations (discussed in detail in Chapter 2).

TABLE 8.1 The principle phases and sub-phases of periodisation

Training phase	*Preparatory phase*		*Competitive phase*
	GPT	*SSPT*	
Phase objective	• ↑ work (aerobic and anaerobic) capacity • ↑ Neuromuscular functioning • Refine technique	• Develop sport-specific biomotors • Develop sport-specific energy metabolism	Maintain biomotor conditioning

Notes: GPT = general physical training; SSPT = sport-specific physical training

The importance of the preparatory phase is highlighted by Zatsiorsky and Kraemer (2006) who use the analogy "soon ripe, soon rotten". Along with data from Fry et al., (2000b) and Stone et al., (2007) this suggests that the average training intensity is inversely correlated with (1) the time a

performance peak can be maintained, (2) the height of that performance peak and (3) the rate of detraining (Figure 8.2).

The S&C coach should note that the science and practice of periodisation is largely based on hypothesis-generating studies, anecdotal evidence and related research (Cissik, Hedrick, & Barnes, 2008; Fleck, 1999; Fry, Morton, & Kreast, 1992; Plisk & Stone, 2003; Stone et al., 1999a). In addition, most studies involved only short-term experimental periods (e.g., five to sixteen weeks) and subjects with limited training experience (Cissik, Hedrick, & Barnes, 2008; Fleck, 1999; Fry, Morton, & Kreast, 1992; Plisk & Stone, 2003; Stone et al., 1999a). However, despite these challenges to an evidence-based ideology, there is enough anecdotal evidence, case-study reports and empirically similar research to advocate its use across all population groups.

RECOVERY AND ADAPTATION

Mesocycle blocks are usually arranged in a 3:1 loading paradigm (Figure 8.3), whereby the load (volume or intensity depending on the goals of the phase) gradually increases for the first three microcycles (weeks) before an unloading phase in the fourth (creating the typical undulating appearance of periodised programmes). The unloading phase reduces accumulated fatigue, thereby allowing adaptations to manifest (Haff, 2004a; Haff, 2004b; Plisk & Stone, 2003). The importance of appropriately planned work to rest ratios (with respect to training sessions) should be noted, with Plisk and Stone (2003) suggesting that the greater the number of progressive loading steps, the greater the number of unloading steps required, e.g., a 6:2 paradigm. Since the majority of training adaptations take place during recovery periods (Haff, 2004a), the need to reduce accumulated fatigue to facilitate the adaptation processes cannot be understated.

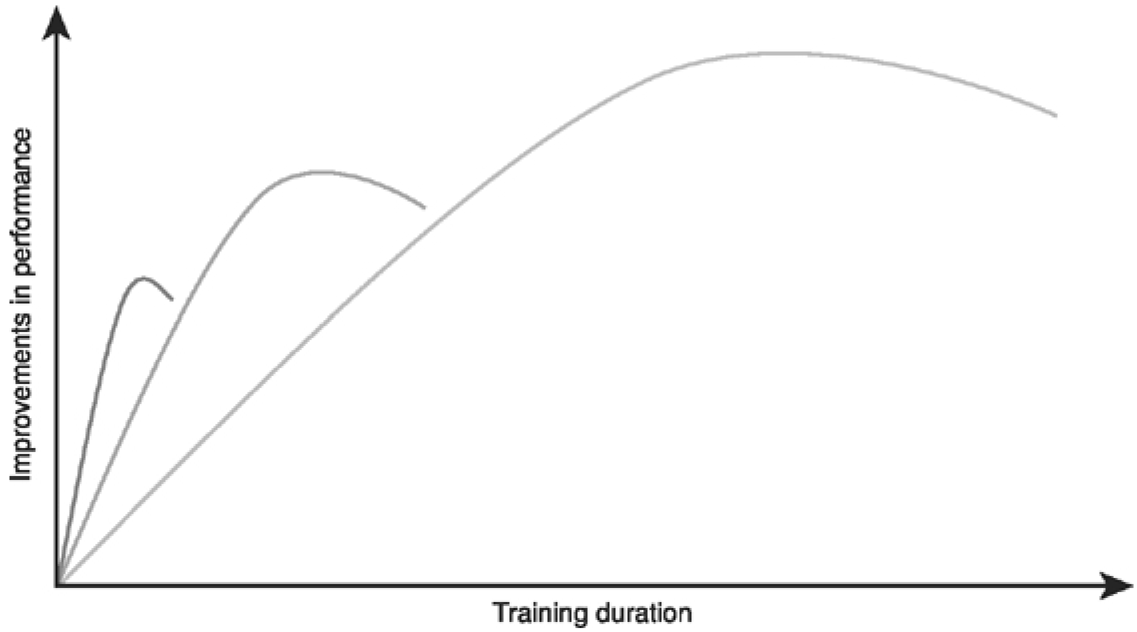

FIGURE 8.2 Soon ripe, soon rotten. Training intensity is inversely correlated with (1) the time a performance peak can be maintained, (2) the height of that performance peak and (3) the rate of detraining. Adapted from Stone et al. (2007).

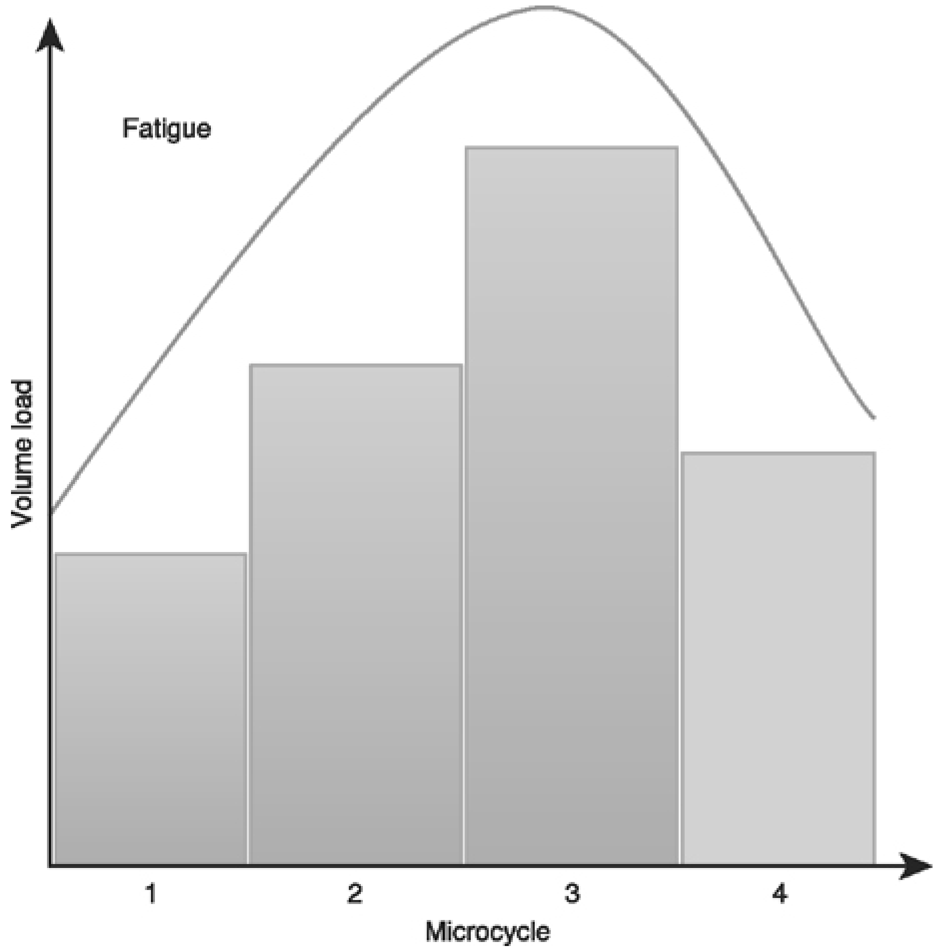

FIGURE 8.3 The 3:1 loading paradigm, illustrating the increase and then dissipation of excessive fatigue.

The importance of recovery phases for the purposes of adaptation is well established (Haff, 2004a; Haff, 2004b). The S&C coach must therefore ensure that work to rest ratios are appropriately planned (e.g., utilising the 3:1 step loading paradigm) to avoid excessive fatigue and a reduced stimulus for adaptation. According to Stone et al. (2007), this trade-off is described by three principle theories: (1) Selye's general adaptation syndrome (GAS), (2) stimulus-fatigue-recovery-adaptation theory (SFRA) and (3) the Fitness-Fatigue theory (Fit-Fat).

General adaptation syndrome

The GAS paradigm describes the body's physiological response to stress, which, according to Selye (1956), is the same despite the stressor. The GAS

assumes three distinct phases during stress, which, for the following example, will be an exercise training session. The alarm phase (phase 1) represents the recognition and initial response to the session. This may be in the form of fatigue, stiffness or DOMS (delayed onset of muscle soreness), for example. The resistance phase (phase 2) is then initiated in which the body is returned to either its pre-exercise session homeostasis or its new adapted higher state (i.e., supercompensation occurs). Finally, and assuming the accumulation of stress is too great (e.g., the absence of an unloading week), the exhaustion phase (phase 3) occurs and may be considered synonymous with overtraining if it continues over a prolonged period (Stone, Stone, & Sands, 2007). The GAS is depicted in Figure 8.4.

Stimulus-fatigue-recovery-adaptation theory

The SFRA concept (Verkhoshansky, 1981; Verkhoshansky, 1979; Verkhoshansky, 1988) suggests that fatigue accumulates in proportion to the magnitude and duration of a stimulus. Then, following the stimulus, e.g., an exercise session, the body is rested enabling fatigue to dissipate and adaptations (often referred to as supercompensation) to occur. This concept also suggests that if the stress is not applied with sufficient frequency (also known as density), detraining (also known as involution) will occur. It is also important to note that if competition frequency is high, then training frequency will have to reduce to permit appropriate recovery. Moreover, involution time is influenced by the length of the preparation period (Stone, Stone, & Sands, 2007), with greater training programme duration increasing the duration of the residual effects (see Figure 8.2) (Zatsiorsky & Kraemer, 2006). In addition, and by virtue of this, the duration of subsequent preparation phases can progressively decrease. The importance of preparation has been previously discussed within this chapter. The SFRA concept is illustrated in Figure 8.5.

The SFRA concept is also used to describe the supercompensation observed following periods of planned overreaching (Verkhoshansky, 1981; Verkhoshansky, 1988). For example, the accumulation of fatigue from the sequential execution of similar training sessions (i.e., a concentrated, primarily unidirectional loading of, for example, strength/power training), usually with a progressive increase in volume, is superimposed on one another. This leads to excessive fatigue and acutely (~4 weeks) diminished

strength and power capabilities. However, following the return to normal training, or a ‘de-load’ period (and by virtue of a delayed training effect phenomenon), they then rebound beyond their initial values (Fry, Webber, Weiss, Fry, & Li, 2000b; Stone & Fry, 1998.). This strategy, however, is reserved for elite level athletes whose window for adaptation is small and therefore requires more intense interventions to bring about a supercompensation response (Bompa & Haff, 2009). Planned overreaching strategies are briefly discussed later in this chapter.

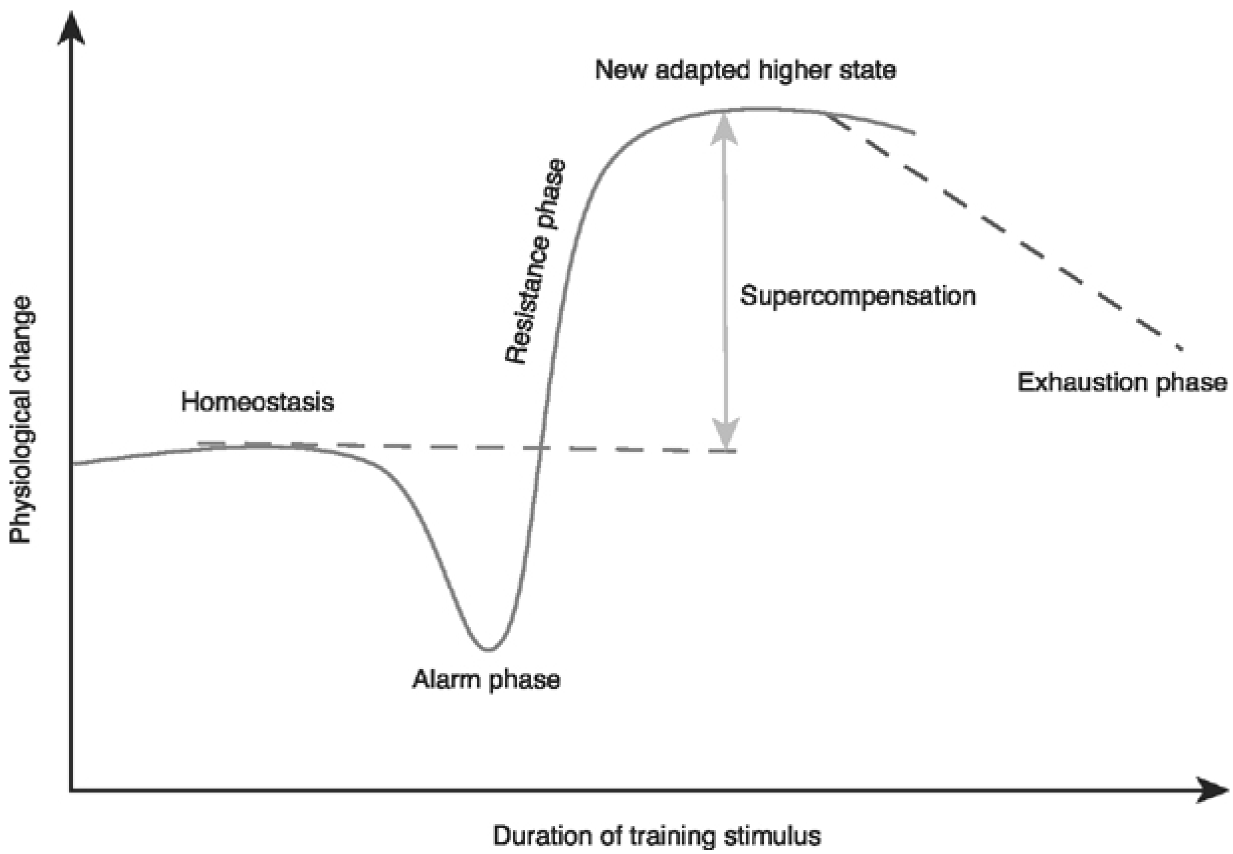

FIGURE 8.4 The general adaptation syndrome.

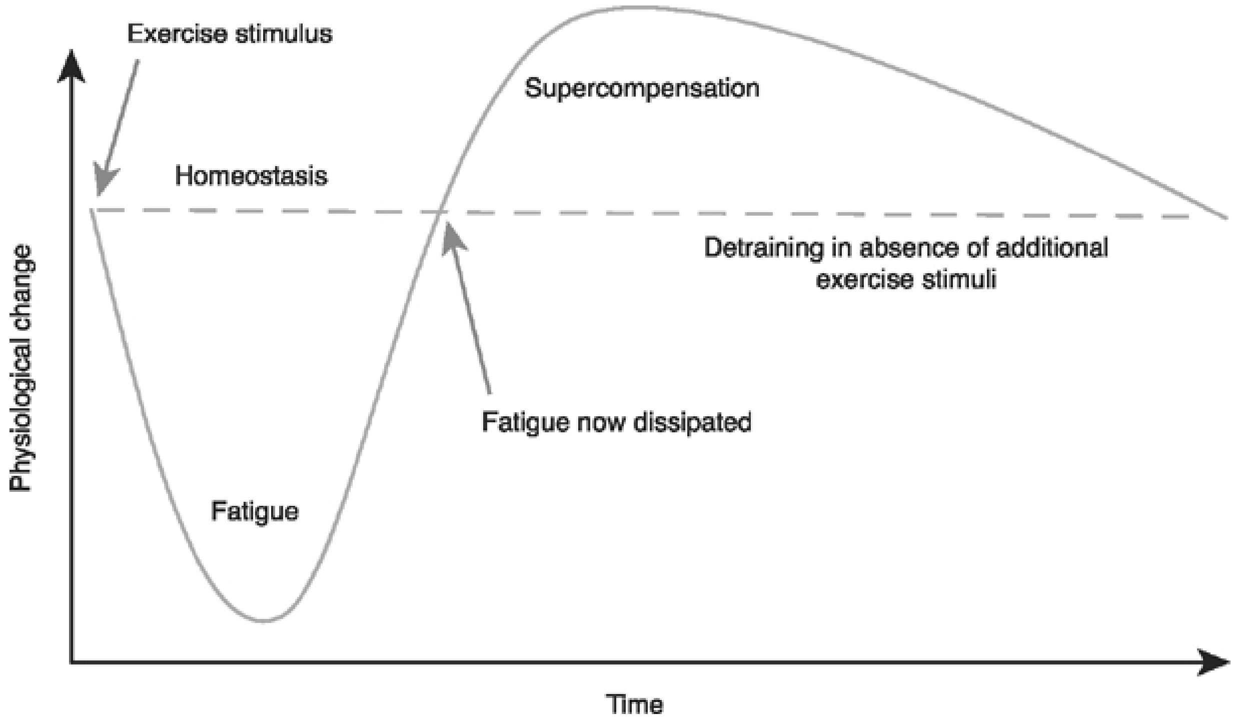

FIGURE 8.5 The stimulus-fatigue-recovery-adaptation concept.

Fitness-Fatigue paradigm

Currently, this is the most prevailing theory of training and adaptation (Chiu & Barnes, 2003; Plisk & Stone, 2003; Zatsiorsky & Kraemer, 2006) and is considered the basic tenet of a taper (discussed later in this chapter) (Mujika & Padilla, 2003). According to this paradigm, athlete preparedness may be evaluated based on the principle after-effects of training: fitness and fatigue (Zatsiorsky & Kraemer, 2006). Unlike the GAS and SFRA concepts, which assume fitness and fatigue share a cause and effect relationship, the Fitness-Fatigue model suggests they demonstrate an inverse relationship. This implies that strategies that maximise fitness and minimise fatigue will have the greatest potential to optimise athlete preparedness (Stone, Stone, & Sands, 2007). The Fitness-Fatigue concept is illustrated in Figure 8.6.

An additional key difference between the Fitness-Fatigue concept and the aforementioned models, is that it differentiates between the actions of various stressors, such as neuromuscular and metabolic stress (Chiu & Barnes, 2003), implying that the after-effects of fitness and fatigue are exercise specific (Stone, Stone, & Sands, 2007; Zatsiorsky & Kraemer, 2006). This suggests that if the athlete is too tired to repeat the same

exercise with acceptable quality, they may still be able to perform an alternative exercise to satisfaction (Figure 8.7), which also aids in reducing monotony for athletes. This, for example, provides the basic tenant to hypertrophy programmes incorporating three- to five–day splits and concurrent training involving both aerobic and resistance workouts.

TRAINING MONOTONY

The lack of change associated with monotonous training volume, intensity or method can predispose an athlete to stagnation (Stone, Keith, Kearney, Fleck, Wilson, & Triplett, 1991; Zatsiorsky & Kraemer, 2006). Also, as described by the principle of diminishing returns (Zatsiorsky & Kraemer, 2006), as an athlete improves in whichever attribute they are developing, the room for adaptation decreases and therefore so does the rate of adaptation (see Figure 8.8). It is, therefore, of upmost importance to incorporate variability within the design of periodised S&C plans, and serves as the rationale for the regular application of novel and semi novel tasks (exercise deletion and representation) (Stone, Stone, & Sands, 2007); Table 8.2 illustrates how this may be incorporated within a periodised plan. As a final word of caution, however, too much variability can reduce the opportunity for the body to adapt to a given stimulus and reduce the development of skill acquisition (Bompa & Haff, 2009).

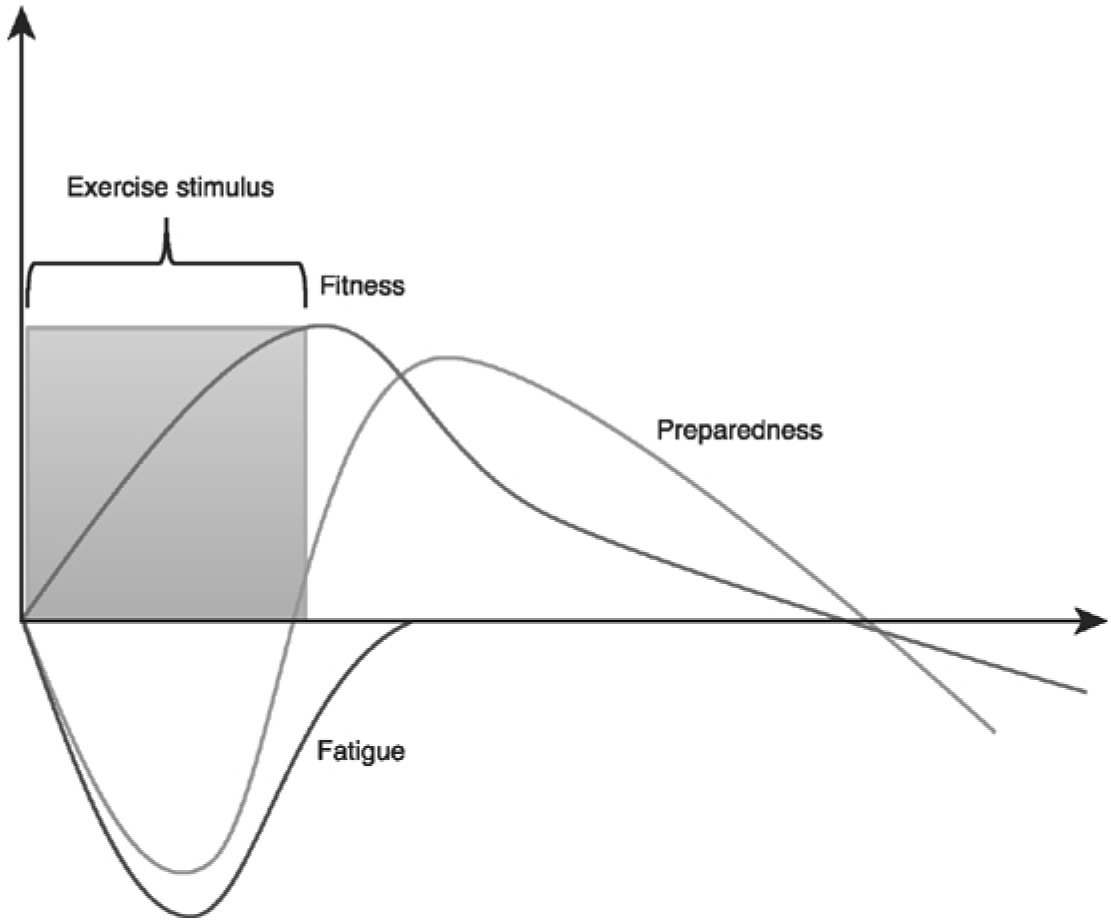

FIGURE 8.6 The Fitness-Fatigue paradigm.

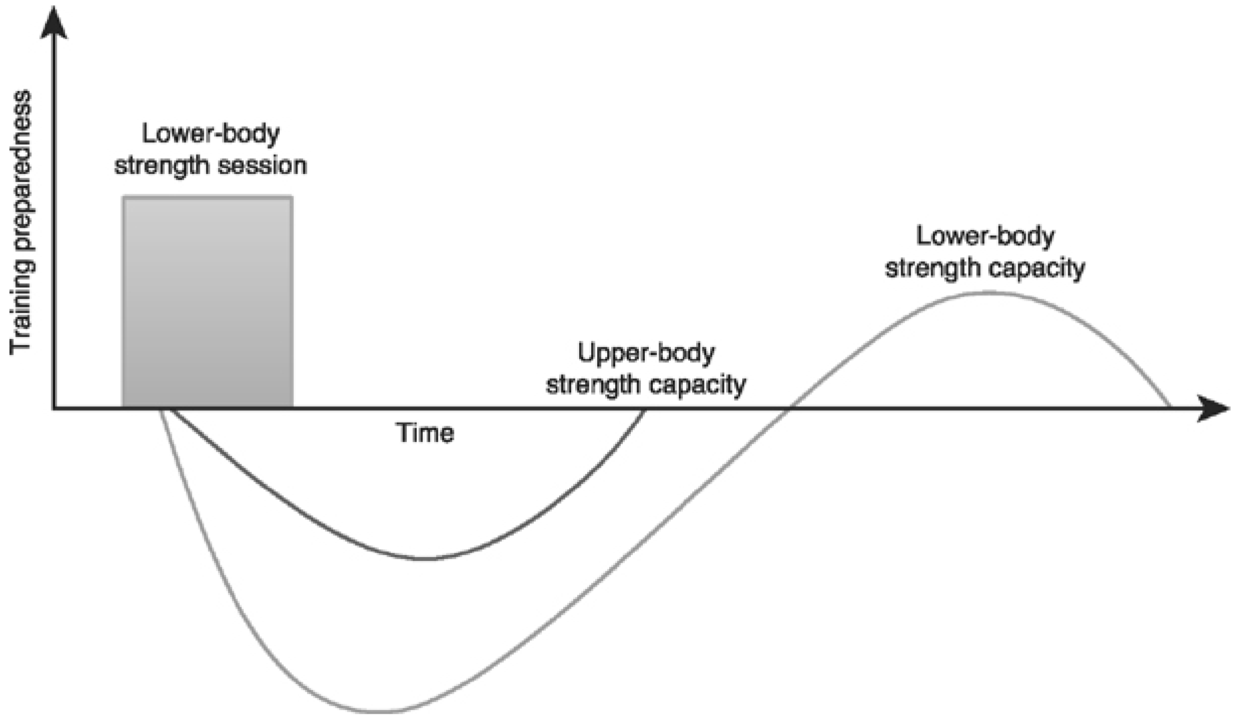

FIGURE 8.7 Athlete preparedness based on the specific form of fatigue. Adapted from Zatsiorsky and Kraemer (2006).

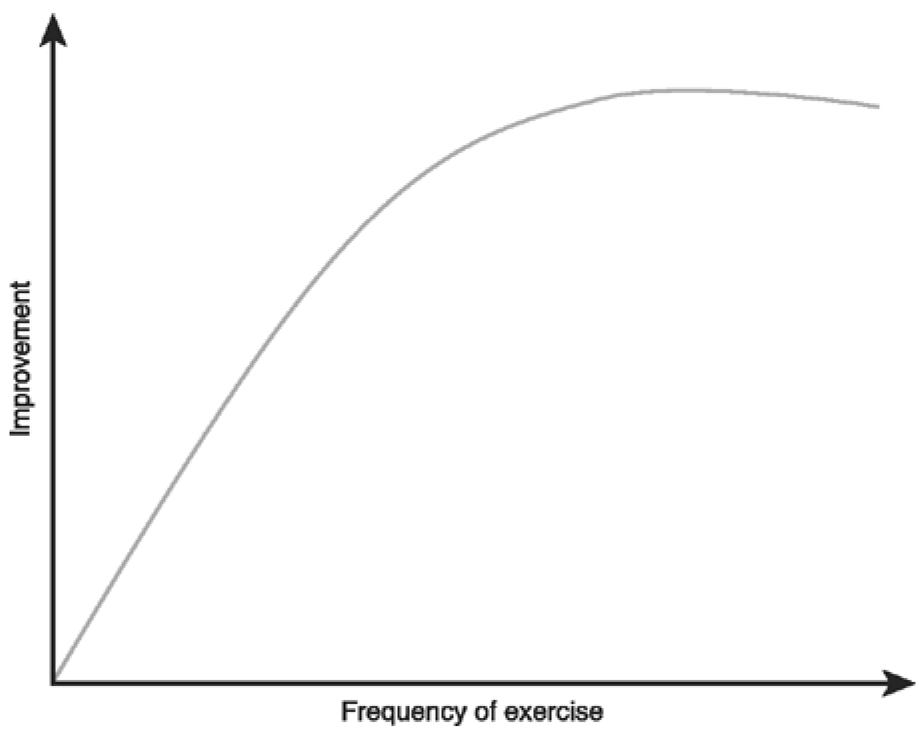

FIGURE 8.8 The principle of diminishing returns.

TABLE 8.2 Exercise deletion and representation

Exercise	*Countermovement Jumps (CMJ)*	*Delete CMJ from programme, replace with drop jump*	*Reintroduce CMJ into programme*
Mesocycle	1	2	3

APPLICATION OF PERIODISATION

Basic Model of Periodisation

The type of periodised model used should reflect the S&C training age of the athlete and not their competition age or rank. It is considered prudent, therefore, to initiate S&C programmes with basic periodised models. These generally entail little variation and relatively flat workloads (Stone, Stone, & Sands, 2007), with the main emphasis being on the logical and thus potentiated progression of biomotors (e.g., strength-endurance " strength " power). Figure 8.9 illustrates a basic model.

As an example of this basic strategy, the athlete completes a hypertrophy/strength-endurance phase for six microcycles (i.e., six weeks or one mesocycle), a strength phase for four microcycles and then a power phase for four microcycles (Table 8.3). Note that the strength-endurance phase is longest because volume is considered a key stimulus for hypertrophy, and is also required to sufficiently increase work capacity, ready for the subsequent phases. Each phase (dependent on the prescribed volume loads) may be further separated by an unloading week, as may happen following the power phase and before the competition. In addition, heavy and light days (with respect to volume as changing intensity will alter the stimulus for strength adaptations) may still be prescribed. This strategy, considered appropriate for athletes with a low S&C training age, introduces them to S&C (i.e., the merits of and the required discipline) and periodisation (i.e., the need to systematically alter the emphasised biomotors and a quality over quantity approach) and enables them to get a "feel" for gym-based training interventions as well as developing their associated technique. As a final note on this basic model (which is actually applicable to all models), to ensure the athlete gets the most out of each phase, the S&C coach should ensure they are technically sound to perform the exercise of each phase before progressing onto it. For example, power

cleans and snatches may be part of the power phase, however, the athlete may have to start practicing and developing them, along with their derivatives, in the strength-endurance phase and maintaining them in the strength phase. In the strength-endurance phase, cluster sets might be used, for example, to ensure maintenance of technique and velocity (Tufano et al., 2016). In the strength phase, weightlifting pulling derivatives using loads ≥ 100% 1RM power clean might be used, as force production is key to their effective use during the power phase (Suchomel, Comfort, & Stone, 2015; Suchomel, Comfort, & Lake, 2017).

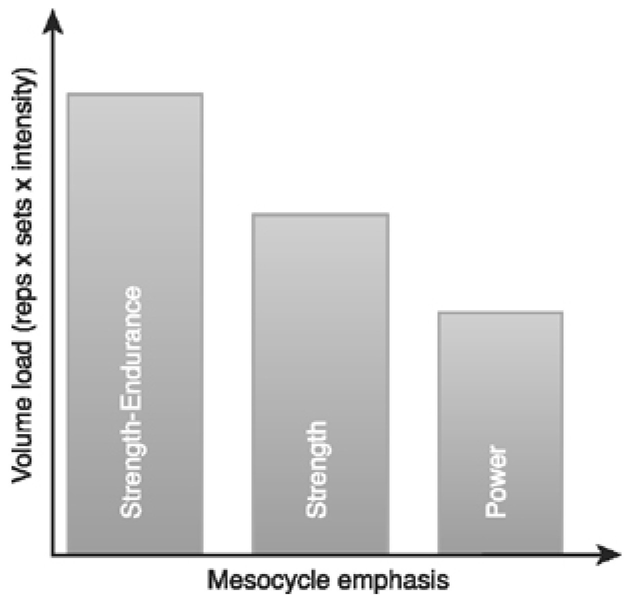

FIGURE 8.9 Basic model of periodisation entailing little variation and relatively flat workloads.

TABLE 8.3 Example sessions used as part of a basic periodised model

Example hypertrophy session	*Example strength session*	*Example power session*
Intensity: 3 × 8–15 (60–75% 1RM), working toward failure, < 3 min between sets and exercises	**Intensity:** 4 × 4 @ 4–6RM (~85–90% 1RM), > 3 min between sets and exercises	**Intensity:** Intensity: 5 × 3 @ variable loads, > 3 min between sets and exercises
Exercises: Squats, Romanian deadlift, bench press, pull-ups. Weightlifting and plyometric techniques may be developed as part of the warm-up		**Exercises:** Clean (70–90% RM), jump squats (0–50% 1RM), plyometrics (body mass) and medicine ball throws. Strength may be maintained with 3 × 3 squats @ 85–90% 1RM

Note: Volume load presented as sets × reps

Intermediate Model of Periodisation

As the athlete's S&C age advances and adaptations begin to plateau, greater variability becomes paramount. In addition, due to the enhanced work capacity of the athlete, greater volume loads are undertaken and thus the need for planned recovery sessions. The periodised programme begins to evolve into wavelike increases in volume loads (Matveyev, 1972; Matveyev, 1977) that typically fluctuate at the microcyclic level (Stone et al., 1999a; Stone et al., 1999b). This is referred to as summated microcycles and is usually represented as the 3:1 paradigm previously discussed. In addition, and due to the need to incorporate variability, each microcycle can incorporate multiple biomotors (e.g., strength, power and speed work), some for the purpose of maintenance and potentiation, and others for the purpose of development and adaptation. Additional methods of incorporating variability and thus adaptation include inter-session variability (e.g., heavy/high volume and light/lower volume days and exercise deletion and re-presentation methods) and intra-session variability (e.g., cluster sets and postactivation potentiation protocols). Figure 8.10 illustrates this traditional approach to designing periodised programmes, which is attributed to Matveyev (1972; 1977). An example intermediate periodised programme is illustrated in Table 8.4.

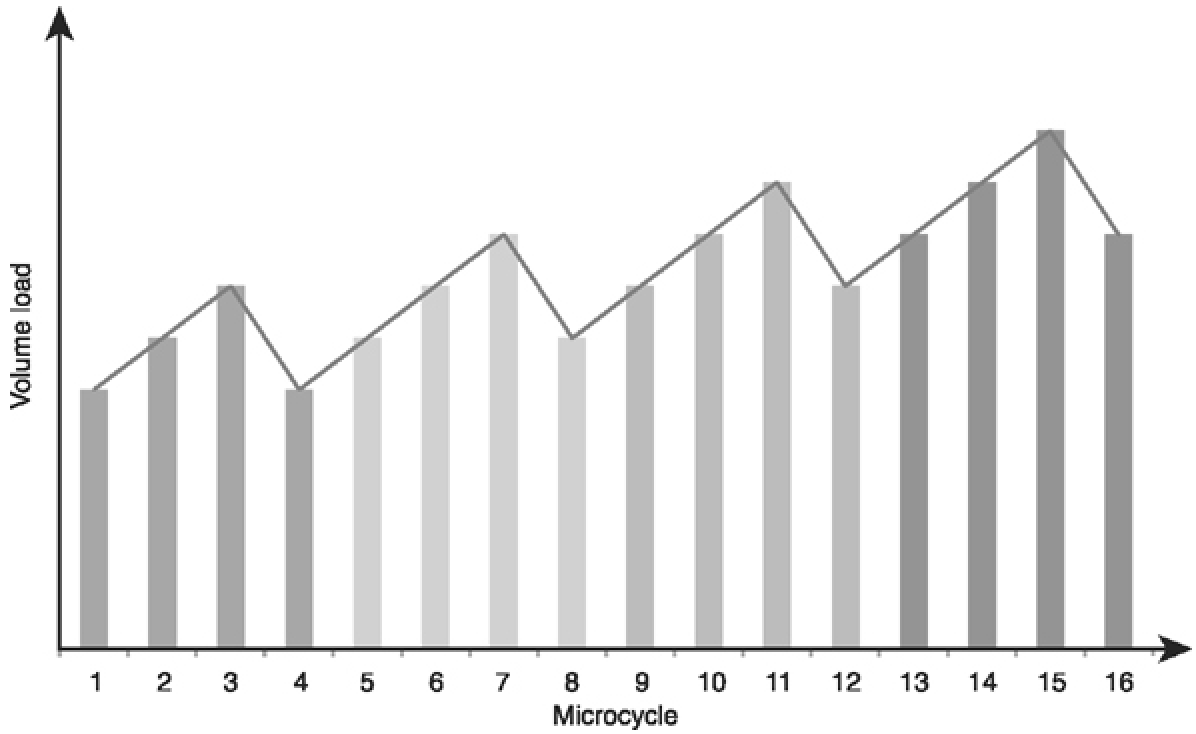

FIGURE 8.10 The traditional, undulating approach to the design of periodised training, which is attributed to the work of Matveyev (1977). Note the 3:1 loading method within each mesocylce.

TABLE 8.4 Two example strength sessions and two example power sessions, which can be implemented as part of an intermediate periodised programme

Strength session 1	*Strength session 2*	*Power session 1*	*Power session 2*
Back squats (5 × 3 ~90% 1RM)	*Power clean (3 × 3 ~ 80% 1RM)	Power snatch from hang (5 × 3 ~80% 1RM)	Power clean from hang & split jerk (5 × 3 ~75% 1RM)
*Jump shrugs (3 × 5 ~35% 1RM)	Split Squat (3 × 3 ~85% 1RM)	*Deadlifts (3 × 3 ~85% 1RM)	*Front squats (3 × 3 ~85% 1RM)
Bent over row (3 × 5 ~85% 1RM)	Romanian dead lift (3 × 3 ~85% 1RM)	CMJ (5 × 5 (body mass))	Drop jumps (5 × 5)
Bench press (3 × 5 ~85% 1RM)	Pull-ups (3 × 3 ~85% 1RM)	*Pull-ups (3 × 3 ~85% 1RM)	*Bench press (3 × 3 ~85% 1RM)

Notes: Volume load presented as sets × reps; * used to develop/maintain technique and strength/power

Advanced model of periodisation

As the athlete's S&C age advances further still, and the windows of adaptation begin to diminish further, more advanced strategies are required which incorporate yet more variability and greater volume loads. The majority of the emphasis is now placed on the prescription of volume loads through advanced strategies such as the conjugated system (Figure 8.12; also known as the coupled successive system) (Verkhoshansky, 1986). Because this places the athlete dangerously close to the overtraining syndrome, athletes undertaking this system must be able to tolerate very high volume loads (Plisk & Stone, 2003) and the S&C coaches applying these interventions must be highly skilled. Furthermore, it may be advisable to ensure athletes have at least 2 years formal S&C experience, with associated strength adaptations, as this is usually associated with increases in the anabolic environment of the body (by virtue of increased testosterone relative to cortisol), and thus greater tolerance to demanding training (this is discussed further in Chapter 4).

The conjugate system involves periods of planned overreaching followed by periods of restitution (Plisk & Stone, 2003). Plisk and Stone (2003) suggest that this is best implemented in blocks of four microcycles with only one primary emphasis (e.g., strength), and maintenance loads allocated to other abilities (e.g., speed/power). This system aims to saturate the emphasised training stress, causing cumulative fatigue and concurrent decreases in performance; this of course can be difficult within team sport environments where fixture congestion is common (e.g., soccer, basketball). Then, during the following restitution blocks, the emphasis is reversed (Figure 8.11). For example, the volume load for strength training markedly drops whilst that for speed work is moderately increased. By virtue of a delayed training effect phenomenon, the athlete's strength capabilities undergo supercompensation. A practical example of the conjugate system, adapted from the work of Plisk and Stone (2003) and Stone et al. (2007), is illustrated in Table 8.5.

Support for the conjugate system may be gleaned from studies investigating the response of the endocrine system to prolonged (≥ 3 weeks) and severe increases in volume load (Hakkinen, 1989; Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Pendalay & Kilgore, 2001; Ratamess et al., 2003; Fry, Webber, Weiss, Fry, & Li, 2000b). In general, these studies report significant decreases in resting/pre-exercise testosterone concentration and the testosterone:cortisol ratio, followed by supernormal

levels and corresponding performance improvements upon returning to normal volume loads with a subsequent taper. These findings are considered significant as testosterone concentration and the testosterone:cortisol ratio are indices of the anabolic/catabolic state of the body (Plisk & Stone, 2003; Fry, Kraemer, Stone, Koziris, Thrush, & Fleck, 2000a). As a word of warning, however, practitioners should limit the duration of these concentrated blocks so that an overtraining syndrome does not develop (Plisk & Stone, 2003). Also, S&C coaches should be attentive to the potential signs and symptoms of overtraining with each passing week (Foster, 1998; Jones, 1991; Stone, Keith, Kearney, Fleck, Wilson, & Triplett, 1991).

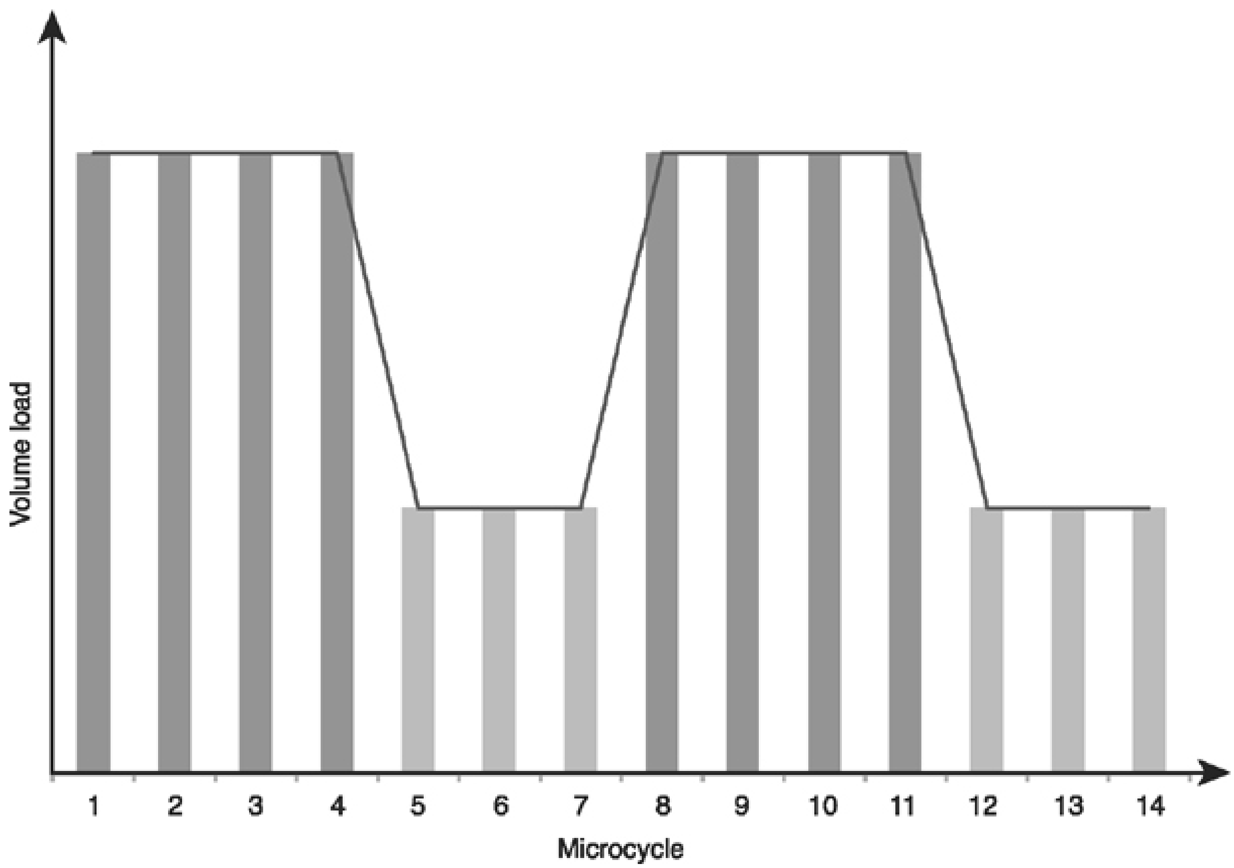

FIGURE 8.11 The conjugate sequence system pioneered by Yuri Verkhoshansky (1986).

TABLE 8.5 A practical example for applying and adapting the conjugate system

Training emphasis	*Accumulation block 1*	*Restitution block 1*	*Accumulation block 2*	*Restitution block 2*
Duration	4 weeks	2–3 weeks	4 weeks	2–3 weeks

Strength and power training	16 sessions @ 4d/wk	4–6 sessions @ 2d/wk	16 sessions @ 4d/wk	4–6 sessions @ 2d/wk
Speed and agility training	8 sessions @ 2d/wk	9 sessions @ 3d/wk	8 sessions @ 2d/wk	9 sessions @ 3d/wk

MAINTENANCE PROGRAMMES

Maintaining peak performance for 35 weeks

The traditional periodisation strategies identified above are concerned with athletes who need to peak for a single or acute (< 2 weeks) phase of competitions, e.g., track athletes and martial artists. Some athletes, however, especially team sport athletes, must reach their peak as part of pre-season training, and then maintain it for periods of up to 35 weeks, ideally peaking for the final.

For example, Kraemer et al. (2004a) showed that both starting and non-starting soccer players experienced reductions in sport performance over an eleven-week period of the competitive season. Although more pronounced in the starters, the fact that performance reductions were observed in all players indicates that performance adaptations may be independent of total match play and that the volume load of practices/S&C sessions should be carefully evaluated. Of significance was the fact that a catabolic environment (increased cortisol and decreased testosterone) was initiated in the pre-season and not obviated throughout the competition phase. This may have determined the metabolic status of the players as they entered the competitive period. While this may be exclusive to the training approach of collegiate soccer, or those that require athletes to get into shape quickly, the need for athlete restoration, particularly as they enter the competitive phase, can be noted.

Further challenges associated with maintenance programmes may be gleaned from studies undertaken by Kraemer et al. (1989) and Aldercrentz et al. (1986). These investigators reported that sprint running increases circulating concentrations of cortisol and decreased concentrations of plasma testosterone. Therefore, for sports such as rugby and soccer, which may be categorized as high-intensity intermittent exercise with a prevalence of repeated bouts of maximal effort sprints, it is likely that an adverse

metabolic environment will present itself if training programmes are not appropriately periodised.

Non-traditional approach to periodisation

It has been suggested that while the traditional form of periodisation (discussed above) is appropriate during the off- and pre-season, a non-traditional form of periodisation is more viable to team sports during the in-season (Gamble, 2006; Hoffman, Kraemer, Fry, Deschenes, & Kemp, 1990; Kraemer et al., 2003; Kraemer et al., 2004b; Kraemer et al., 2000). At times, this may be out of necessity because of its ability to adapt to sports competition calendar and its ease of administration within long seasons (Hoffman, Kraemer, Fry, Deschenes, & Kemp, 1990; Kraemer et al., 2003; Kraemer et al., 2000). This form of periodisation involves changes in volume loads and biomotor emphasis on a session to session basis. An example of a non-traditional periodised programme is illustrated in Table 8.6. One of the merits of this system is suggested to be the ease with which sessions can be quickly tailored to the competition schedule of the athlete (Haff, 2004a). If, for example, a competition is suddenly cancelled or arranged, the athlete can switch to the heavy or light training day respectively. In addition, a microcycle and a mesocycle can be defined by the number of completed sessions or rotations, respectively, of the prescribed programme.

TABLE 8.6 Example microcycle completed as part of a non-traditional periodisation strategy. Note that a mesocycle may be considered complete following a set number of rotations and athletes can rearrange the order based on competition scheduling. Finally, hypertrophy sessions are avoided due to its higher training load requirements

Day	*Monday*	*Wednesday*	*Friday*
Emphasis and volume load	Pushing strength: 4 × 4 @ 4–6 RM	Pulling strength: 4 × 4 @ 4–6 RM	Power: 5 × 3 @ variable loads
Example exercises	Squats, bench press and overhead press	Romanian deadlift, pull-ups and barbell row	Weightlifting and derivatives and plyometrics

Finally, for the purposes of maintenance, a training frequency of two days per week is often recommended for training during the competitive

phase (Ebben & Blackard, 2001; Ebben, Hintz, & Simenz, 2005; Gamble, 2006; Haff, 2004b; Simenz, Dugan, & Ebben, 2005). However, including even two S&C sessions a week to team sport players involved in regular competition may prove difficult. Gamble (2006) suggests that the issue of limited training time may be addressed by combining S&C training into sport practice. For example, speed, agility and plyometrics training can be included into team practices, and metabolic conditioning can be maintained through game-related conditioning methods. In addition, the skill element specific to each, particularly the latter example, encourages its use by the sport coaches (Gamble, 2004). This tactical metabolic training approach can be structured according to work:rest ratios of the specific sport (Gamble, 2007; Plisk & Gambetta, 1997) and dominant energy systems.

THE TAPER

The progressive increases in the volume load of periodised S&C programmes are likely to accumulate excessive fatigue and overstress the neuroendocrine system. This will reduce the stimulus for adaptation (as previously discussed) and lead to adverse circulating hormonal concentrations (Fry & Kraemer, 1997). However, a reduction in training with a concomitant optimal anabolic environment (or reduced catabolic processes) induced by a taper could potentially enhance performance (Izquierdo et al., 2007). The taper requires a reduction in the volume (i.e., exercises, sets or repetitions) of training in the final days before important competition, with the aim of optimising performance (Bosquet, Montpetit, Arvisais, & Mujika, 2007). It should be stressed that the objective of the taper is to dissipate the accumulated fatigue (enabling performance-enhancing adaptations to become apparent), rather than advance the athlete's level of fitness (Mujika & Padilla, 2003). Significant improvements after tapering have been reported in numerous sports and Table 8.7 summarises the associated performance gains as summarised by Wilson and Wilson (2008).

TABLE 8.7 Summary of performance gains following a taper. Adapted from the review of Wilson and Wilson (2008)

• 5–6% improvements in criterion competition performance gains.

- Up to 20% increases in neuromuscular function (i.e., strength and power).
- 10–25% increases in cross sectional area of muscle tissue.
- 1–9% improvements in VO_2max (this is likely a consequence of hypervolemia, up to a 15% increase in RBC production and increases oxidative enzyme activity).
- Up to an 8% increase in running economy.
- Serum TST may increase by 5%, with a corresponding 5% decrease in cortisol.
- Catecholamines may be reduced by up to 20%.
- Reduced creatine kinase concentrations (suggestive of decreased muscle damage following a workout).
- A 10% increase in anti-inflammatory immune cells, with a concomitant decrease in inflammatory cytokines.
- Increased muscle glycogen stores (17–34%; often proportional to the reduction in volume load) especially following CHO loading. However, care should be taken to match energy intake with the reduced energy expenditure that characterises the taper.
- Reduced RPE, depression, anger and anxiety and increased vigour.
- Decreased sleep disturbances.

TAPER STRATEGIES

Generally three types of taper are used: a step taper, a linear taper and an exponential taper (Figure 8.12). A step taper involves an immediate and abrupt decrease in training volume, e.g., decreasing the volume load by 50% on the first day of the taper and maintaining this throughout. A linear taper involves gradually decreasing the volume load in a linear fashion, e.g., by 5% of initial values every workout. The exponential taper decreases volume at a rate proportional to its current value (half-life), e.g., by 5% of the previous sessions values every workout. In addition, exponential tapers can have fast or slow decay rates. Also, Bosquet et al. (2007) suggested an additional taper, referred to as a ‘‘2-phase taper’’ which involves a classical reduction in the training load, followed by a moderate increase during the last days of the taper (Figure 8.13). The objective of this strategy is to reduce the athlete’s fatigue before the reintroduction of more prolonged or intense efforts. The efficacy of the 2-phase taper maybe gleaned from anecdotal observations of the progressive improvement in performance often observed in an athlete from the first round of a competition to the final (Thomas, Mujika, & Busso, 2009). This form of taper requires further investigation.

THE OPTIMAL TAPER STRATEGY

As previously mentioned, a taper involves either a reduction in the volume load or a reduction of a combination of the moderators of training, i.e., intensity, volume and frequency. The optimal manipulation of these variables may be best evidenced from the meta-analysis conducted by Bosquet et al. (2007); Table 8.8 summaries their findings measured as effect sizes, for which the scale proposed by Cohen (1988) was used in their interpretation. Accordingly, the magnitude of the difference was considered small (0.2), moderate (0.5) or large (0.8).

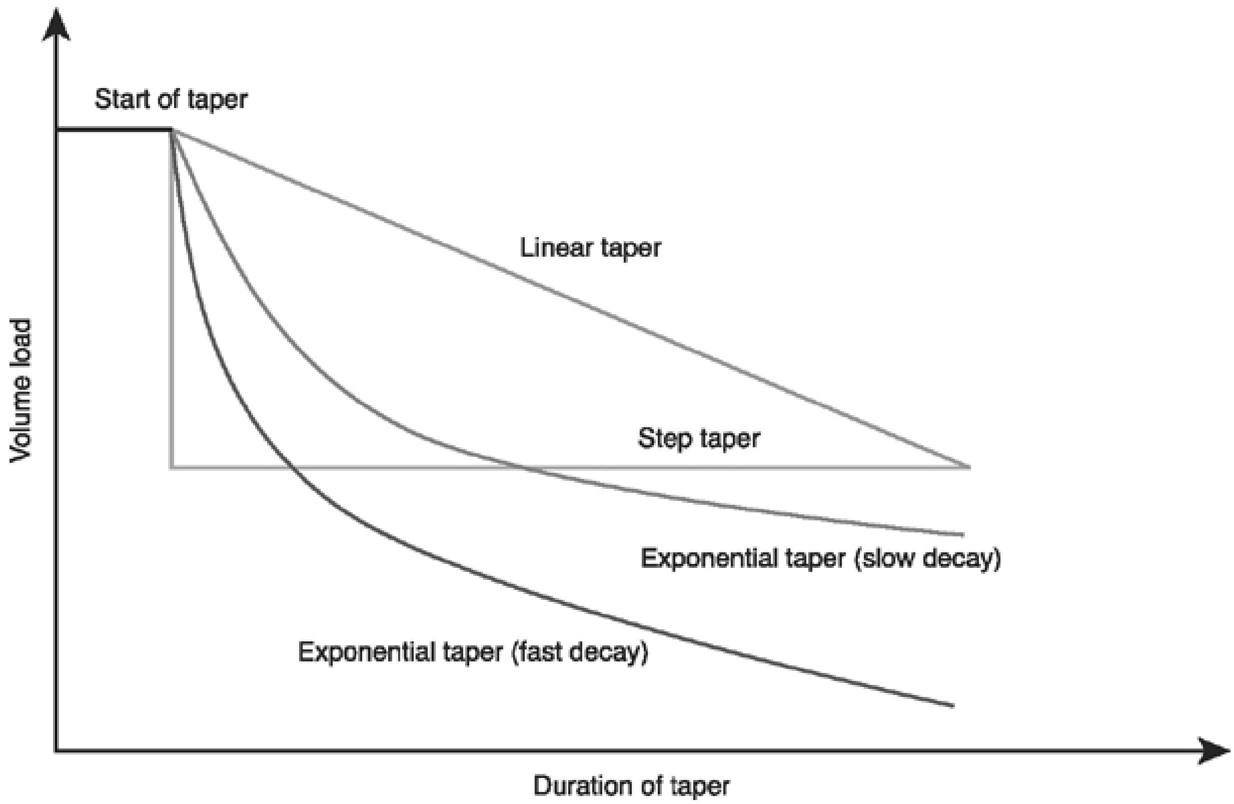

FIGURE 8.12 Schematic representation of the three principle tapering strategies. Adapted from Mujika and Padilla (2003).

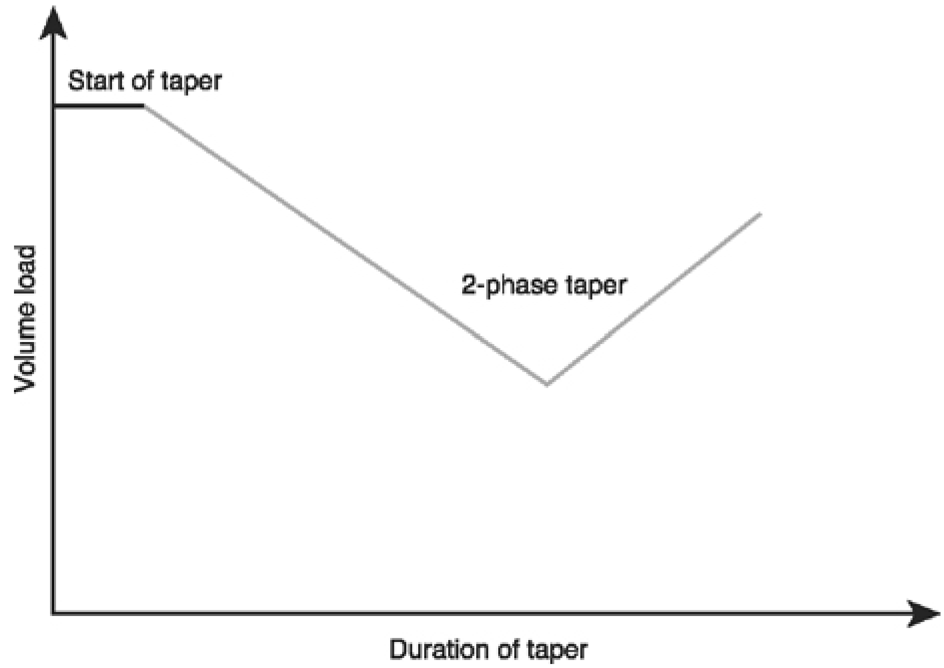

FIGURE 8.13 Schematic representation of the 2-phase taper. Adapted from Thomas et al. (2009).

TABLE 8.8 Effect of training variables on the effect size of taper-induced performance adaptations. Data from Bosquet et al. (2007)

Variable	*Effect size*	*95% CI*	*p*
↓ in volume			
≤20%	–0.02	–0.32–0.27	0.88
21–40%	0.27	0.04–0.49	0.02
41–60%	0.72	0.04–1.09	0.0001
≥60%	0.27	–0.03–0.06	0.07
↓ in intensity			
Yes	–0.02	–0.04–0.33	0.91
No	0.33	0.19–0.47	0.0001
↓ in frequency			
Yes	0.24	–0.03–0.52	0.08
No	0.35	0.18–0.51	0.0001
Duration of taper			
≤7 d	0.17	–0.05–0.38	0.14
8–14 d	0.59	0.26–0.92	0.0005
15–21 d	0.28	–0.02–0.59	0.07

≥ 22	0.31	0.14–0.75	0.18
Pattern of taper			
Step	0.42	–0.11–0.95	0.12
Progressive	0.30	0.16–0.45	0.0001

Notes: CI = Confidence intervals; P = significance value; . = magnitude of the difference was considered small (0.2), moderate (0.5) or large (0.8)

The results from Bosquet et al. (2007) revealed that the optimal taper is two weeks in duration and consists of exponentially reducing the volume of training by 41–61%, whilst maintaining both the intensity and frequency of sessions. It should be noted that the large variability between studies, as suggested by 95% confidence intervals, suggests that not all athletes will respond favourably to this taper prescription, which may be attributable to the differences in training status and accumulated fatigue prior to the taper, i.e., greater volume reductions are necessary when previous training durations are longer and more intense.

SUMMARY AND CONCLUSION

Periodisation represents an optimal strategy for organising S&C programmes. The selected strategy (i.e., basic, intermediate, advanced, non-traditional) should be based on the level of the athlete and the constraints of the competitive season. A common theme throughout all periodisation protocols is the need to manipulate volume loads, progress from general to specific training and to dissipate fatigue, where pre-competition tapers appear evidently beneficial. Also, the use of a taper appears to produce an additional supercompensation effect following the accumulated fatigue of the preceding training programme. For sports engaged in infrequent competition, traditional periodisation may be best. For team sports with long seasons and frequent competitions, non-traditional periodisation may better suit the demands placed on the athletes, with a reduction in volume but not intensity in the training session immediately prior to competition.

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CHAPTER 9

Workload monitoring and athlete management

Tim J. Gabbett

THEORY OF TRAINING MONITORING AND THE "OPTIMUM" TRAINING DOSE

Physical capacity can be improved by means of the biological adaptation feature common amongst living species (Bompa, 1983). Stress, defined as a disturbance from "normal", in a biological system stimulates adaptive responses to restore homeostasis beyond recovery until super-compensation is attained (Selye, 1956). Selye (1956) described this as the general adaptation syndrome, where a stressor results in a sequence of responses (Figure 9.1). The initial response is a negative 'alarm stage' where the physiological state is diminished (fatigue). With adequate recovery, there is a positive resistance response where regeneration occurs, resulting in a super-compensation effect (fitness) (Bompa, 1983; Budgett, 1990; Matveyev, 1981; Morton, 1997). However, if the stress is greater than the organism's adaptive capabilities, exhaustion occurs. The response phase is considered to be proportionate to the magnitude of the stimulus, and with sufficient regeneration, leads to an improved condition (Figure 9.2).

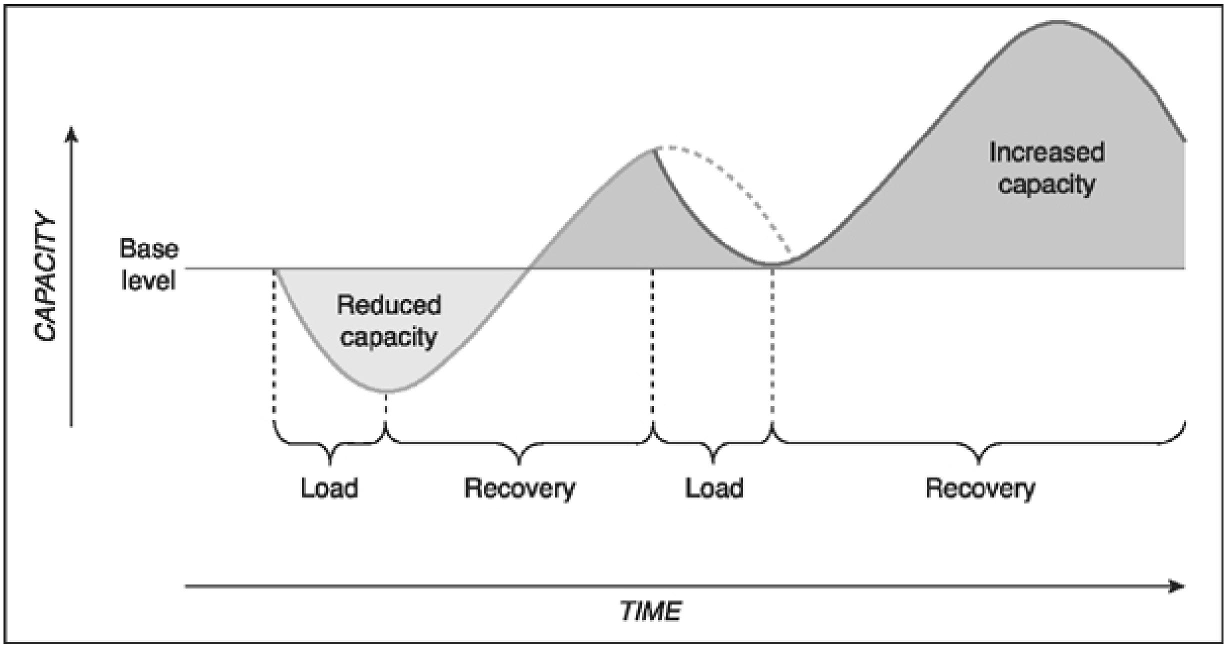

FIGURE 9.1 Biological adaptation through cycles of loading and recovery (adapted from Meeusen, 2013 and Soligard et al., 2016).

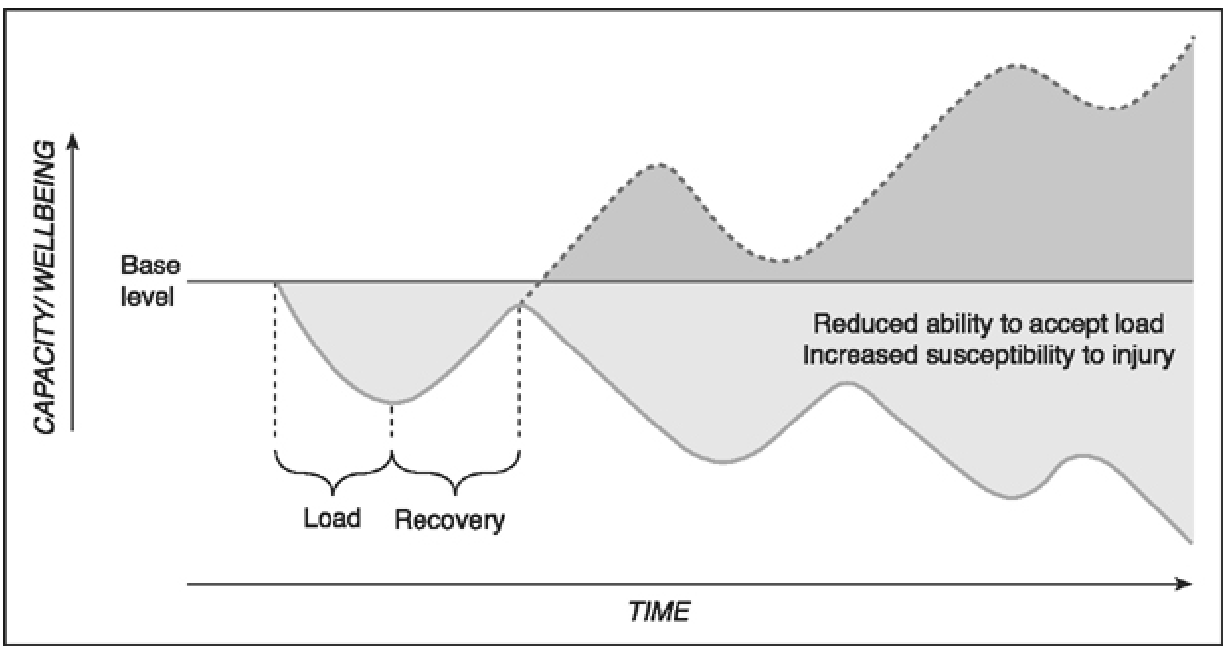

FIGURE 9.2 Biological maladaptation through cycles of excessive loading and/or inadequate recovery (adapted from Meeusen et al., 2013 and Soligard et al., 2016).

An extension of this theory is the Fitness-Fatigue model presented by Banister and colleagues (1975). These authors proposed that performance could be determined from the interaction of fitness and fatigue. They

contended that an exercise stimulus induces two responses, indicated by a positive (fitness) and negative (fatigue) function. However, these responses differ in magnitude and duration, fitness having a smaller magnitude but longer duration (Zatsiorsky & Kraemer, 1995). Provided enough time is given for the negative effect of fatigue to subside between exercise bouts, the cumulative fitness effects of long term training will lead to improved physical capacity (Bompa & Haff, 1999). It has also been proposed that there are fitness and fatigue effects on more than one system of the body (Chiu & Barnes, 2003). Specific stimuli will have different fatigue responses (e.g., musculoskeletal, metabolic, and immunological) and it is the summation of the after-effects of fitness and fatigue on all of these systems that ultimately represents preparedness (i.e., physical capacity). While the individual fitness and fatigue after-effects are independent, attention must be paid to the potential combined and interacting effect of these two factors.

Physical training is necessary to enhance physical capacity; however, adequate periods of recovery are required in order for sufficient regeneration to occur (Budgett, 1990; Meeusen et al., 2006). If a training stress is inadequate, overload will not be achieved and neither will any adaptive response, and therefore athletes will fail to improve their physical condition, whereas a training stress that is too high, and/or with inadequate recovery, will have the negative effects of fatigue accumulation, leading to reduced performance potential (Busso, 2003). Prescribing the optimum training and recovery doses poses a considerable challenge for coaches, sport scientists, and strength and conditioning staff.

Overreaching and overtraining

A negative training state can occur when inadequate recovery is provided in response to physical training programs (Fry, Morton, & Keast, 1991; Kenttä, G., & Hassmén, 1998). The continuous nature and unclear turning point between the positive (performance enhancement) and negative (performance decrement) aspects of training and over-reaching makes overtraining difficult to diagnose (Fry et al., 1991; Kuipers & Keizer, 1988).

For the context of this review, overtraining is used to describe an imbalance between stress (training and non-training) and recovery (Lehmann et al., 1999; Richardson et al., 2008). Successful application of

overtraining, deliberately aiming to stimulate physiological adaptations, is considered functional overreaching (outcome) (Zatsiorsky & Kraemer, 1995). Functional overreaching may involve transient performance incompetence, due to the induced fatigue, but results in an improved condition following short-term recovery periods (days or weeks) (Meeusen et al., 2006). Performance failing to rebound following prolonged intense training and insufficient recovery is termed non-functional overreaching (Meeusen et al., 2006). Amongst the plethora of research investigating the signs and symptoms of non-functional overreaching, a gold-standard diagnosis is lacking (Meeusen et al., 2006). Indicators of non-functional overreaching include performance decrements, severe physical and psychological fatigue including muscle soreness, overuse injuries, and increases in perceived effort, all of which may persist for months (Fry et al., 1991; Meeusen et al., 2006). Furthermore, physiological symptoms such as endocrine changes, increases in heart rate (HR), ventilation and blood lactate concentration for a given workload, increases in resting HR and the slow return of HR after exercise, decrease in maximal oxygen consumption (VO_2 max), decreases in sub-maximal and maximal blood lactate concentration, and decreased work capacity are observed (Genttä & Hassmén, 1998; Kuipers & Keizer, 1988). Importantly, separating acute changes to homeostasis as a response to overtraining from symptoms of non-functional overreaching is dependent on the timing of the assessment.

Overtraining syndrome is the end state of chronic non-functional overreaching with sport-specific performance decrements accompanied by psychological symptoms in the absence of a diagnosable medical condition (Fry et al., 1991). The defining symptom is the inability to correct these with periods of recovery (i.e., the need for complete long-term rest of months or even years). Overtraining syndrome has also been linked to a range of sympathetic and parasympathetic symptoms (Kuipers & Keizer, 1988; Lehmann et al., 1999). The sympathetic symptoms relate to increased sympathetic nervous system activity at rest, such as increased HR, potentially leading to restlessness and excitation (Kuipers & Keizer, 1988). On the other hand, the parasympathetic symptoms are characterized by a predominance in vagal tone or adrenal insufficiency and dominating parasympathetic activity at rest and during exercise (e.g., reduced HR) related to inhibition and depression (Kuipers & Keizer, 1988). Similarly to non-functional overreaching, the continuous nature of overtraining limits

the ability of these isolated symptoms to differentiate overtraining syndrome from overtraining. However, while some physiological and biochemical markers have been shown to confirm staleness, they fail to prevent it due to the continuous nature of overtraining and the delayed feedback often associated with such measures (e.g., time for laboratory analysis) (Hooper & Mackinnon, 1995; Kellmann, 2010).

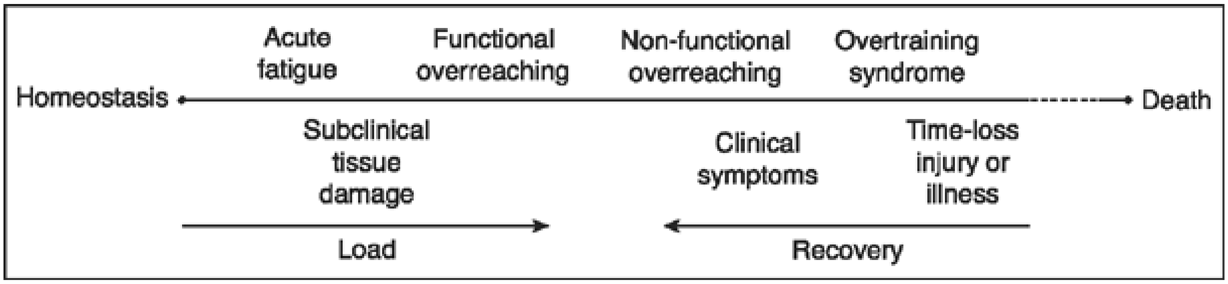

FIGURE 9.3 Well-being continuum (adapted from Fry et al., 1991).

The equivocal data surrounding physiological, biochemical, and immunological measures, and their lack of feasibility and inability to separate functional and non-functional overreaching, restricts their application. As such, currently the most effective and practical way of detecting non-functional overreaching or overtraining syndrome is thought to be via psychological markers and/or performance decrements (Saw et al., 2016). Coaches must carefully monitor athlete workloads and symptoms of well-being in order to adjust the training stimulus when required, and reach a balance between adequate training, under-training, and over-training (Figure 9.3).

External and internal workloads

Sport scientists typically obtain measurements of a prescribed *external* training load (i.e., physical 'work'), accompanied by an *internal* training load (i.e., physiological or perceptual 'response'). External training loads may include total distance run, the weight lifted, or the number and intensity of sprints, jumps, or collisions (to name a few). Internal training loads include ratings of perceived exertion and heart rate. The individual characteristics of the athlete (e.g., chronological age, training age, injury history, and physical capacity) combined with the applied external and

internal training loads determine the training outcome (Impellizzeri et al., 2005).

For example, identical external training loads could elicit considerably different internal training loads in two athletes with vastly different individual characteristics; the training stimulus may be appropriate for one athlete, but inappropriate (either too high or too low) for another. An overweight, middle-aged male will have very different physiological and perceptual responses to an 800m effort than a trained runner. Although the external training load is identical, the internal training load will be much higher in the older, unfit individual! As the dose-response to training varies between individuals, training should be prescribed on an individual basis.

MYTHS AND MISCONCEPTIONS

Can workload information really be used to “predict” injury?

Given the relationship between athlete workloads and injury, a logical assumption is that workload data could be used to “predict” when an athlete is at risk of injury. Over a two-year period, we used the session-RPE (rating of perceived exertion) to model the relationship between training loads and the likelihood of injury in elite rugby league players (Gabbett, 2010). Training load and injury data were modelled using a logistic regression model with a binomial distribution (injury vs. no injury) and logit link function, with data divided into pre-season, early competition, and late competition phases.

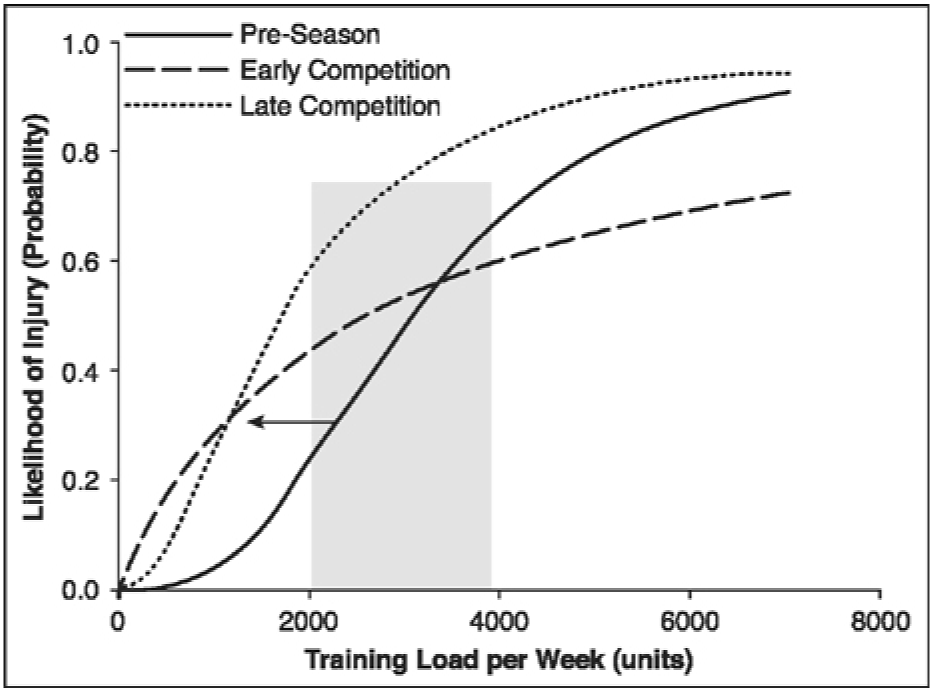

FIGURE 9.4 Relationship between training load, training phase, and likelihood of injury in elite rugby league players (adapted from Gabbett, 2016). *The competitive phase of the season was divided in half to calculate the likelihood of injury during the "early competition" and "late competition" phases.*

Players were 50–80% likely to sustain a pre-season injury within the weekly training load range of 3,000 to 5,000 arbitrary units [RPE x minutes, as above]. These training load 'thresholds' for injury were considerably lower (1,700 to 3,000 session-RPE units/week) in the competitive phase of the season. Importantly, on the steep portion of the sigmoidal training load-injury curve, very small changes in training load resulted in very large changes in injury risk (Figure 9.4).

Training load and injury data were prospectively recorded over a further two competitive seasons in those elite rugby league players. An injury prediction model based on planned and actual training loads was developed and implemented to determine if non-contact, soft-tissue injuries could be predicted. One-hundred and fifty-nine non-contact, soft-tissue injuries were sustained over those two seasons. The percentage of true positive predictions was 62% (N = 121) and the false positive and false negative predictions were 13% (N = 20) and 11% (N = 18), respectively. Players who exceeded the weekly training load threshold were 70 times more likely to test positive for non-contact, soft-tissue injury, while players who did not exceed the training load threshold were injured 1/10 as often. Furthermore,

following the introduction of this model, the incidence of non-contact, soft-tissue injuries was halved (Figure 9.5).

We also analyzed the prevalence of injury and the predictive ratios obtained from the model. The prevalence of injury in this sample of professional rugby league players was 8.6%. If the predictive equation was positive for a given player, the likelihood of injury increased from 8.6% to 86%, and if the results of the test were negative, the likelihood of injury decreased from 8.6% to 0.1%. Furthermore, 87% (121 from 139 injuries) of the 8.6% of players who sustained an injury were correctly identified by the injury prediction model.

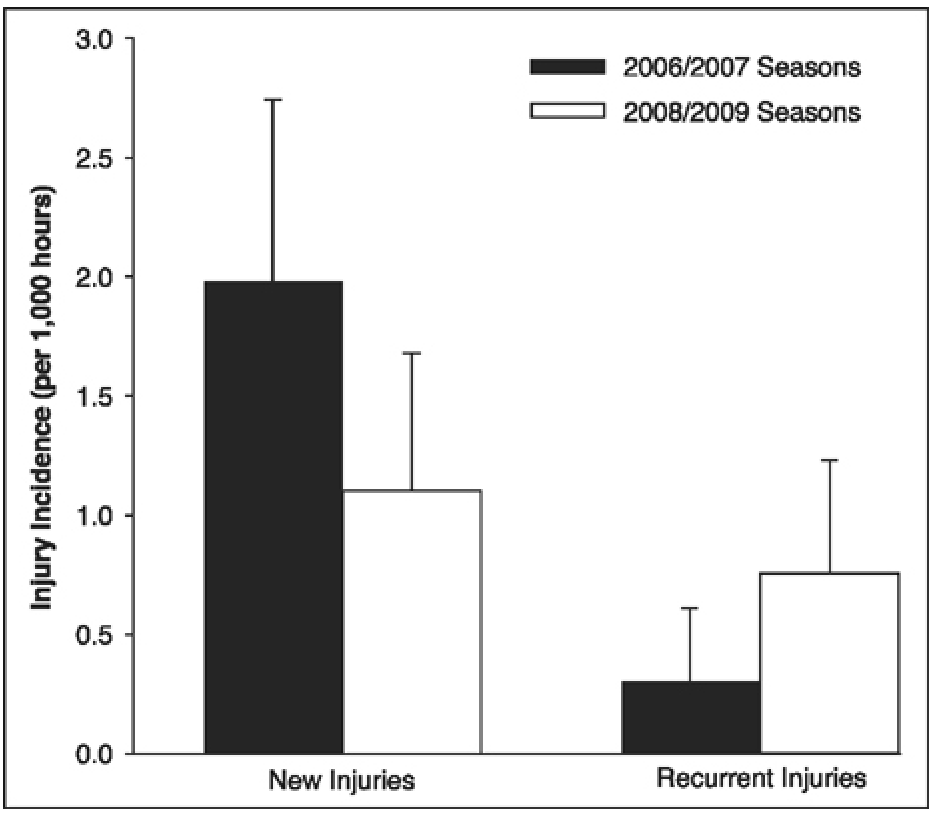

FIGURE 9.5 Incidence of new and recurrent injuries before (2006–2007) and after (2008–2009) the introduction of an injury prediction model designed to reduce training load-related injuries (adapted from Gabbett, 2010).

It is important to recognize that injury "*prediction*" does not mean that injuries can be determined with Nostradamus-like precision! Workload-injury models are based on probabilities; i.e., based on the known relationship between workload and injury, at a given workload (for a given player and point in time), what is the *likelihood* of injury? Although several

commercially available software programs claim to predict training load-related injuries, to date, our study is the only one to predict injury based on workload data, apply that model in a high performance sporting environment, and then report the results in a peer-reviewed journal. We acknowledge that any regression model that predicts injury is best suited to the population from which it is derived, and that non-linear models *may* have greater utility than linear models. In addition, caution should be applied when extrapolating these results to other sports and populations. Despite this potential limitation, these findings provide information on the training dose-response relationship in elite rugby league players, and a scientific method of monitoring and regulating training load in these athletes. Importantly, in a team environment, this approach allows players to be managed on an individual basis.

Is there a "gold standard" workload measure?

With so many diverse external and internal load monitoring tools available, a question commonly asked is, "what 'metrics' should I measure?" The answer to this question will depend largely on the sport. For example, despite both athletes being required to run and throw, high speed running metres is a meaningless metric for baseball pitchers, as is the total number of throws for a football goal-keeper. It is likely that the most appropriate metrics will be associated with performance as well as injury risk. In all likelihood, the optimal measures for each sport, and perhaps each individual, have not yet been described.

It needs to be recalled that the demands of the match will be specific to individual tissues and energy systems for any given athlete's role within any given sport. The rate-limiting tissue and/or energy systems need to be targeted first and foremost both during preparation and monitoring. High chronic training loads on an exercise bike are not the same as high chronic over ground sprinting loads as they will induce different changes in the musculature of the thigh. If the ultimate aim of the sport is repeated-sprint ability, then accrual of high chronic cycling loads (at the expense of high speed running) are likely to reduce performance and increase injury risk.

The session-RPE is most likely the simplest loading metric to apply to athletes across team and individual sports. Increasingly advanced technological solutions are becoming available at an astonishing rate, with

many claims being made regarding the veracity of standard and novel measurements. When considering the purpose of these metrics, we need to return to the primary aims of describing appropriate loads to maximize physical improvement while simultaneously minimizing injury risk. In many situations (e.g., in sub-elite populations), it would appear that the added accuracy provided by the more complex measures are clinically insignificant, and quite possibly not worth the additional investment. As technology continues to improve, this statement will almost certainly need revision, but before investing in expensive technology, performance and medical staff should consider the demands of the sport and whether the technology can measure the critical "metrics" for the sport in question.

Are subjective measures really that valuable?

In a recent systematic review, Saw et al. (2016) reported a poor relationship between subjective and objective markers of athlete well-being. However, subjective measures reflected acute and chronic training loads with superior sensitivity and consistency to objective measures. Subjective well-being was typically impaired with an acute increase in training load, and also with chronic training, while an acute decrease in training load improved subjective well-being. Collectively, these results suggest that subjective markers may provide greater insight into athlete status than objective markers.

Successful implementation of any subjective reporting, be it athlete well-being or session-RPE, is dependent on effective relationships and honest communication between the athlete and coaching staff. Despite the evidence demonstrating that subjective markers may be useful in the athlete monitoring process, the success of these processes are contingent on athlete compliance (i.e., the athlete completing the surveys when required). In addition, a degree of skepticism surrounds both the "honesty" of athlete responses (from coaching staff) and "what is actually done with the results" (from athletes). An obvious, but perhaps poorly understood, consideration with the collection of training load and well-being data is that the data collection alone is not the "end-point" and will not guarantee a positive training outcome. Effective use of this information requires both appropriate analysis of the data and interpretation within the context of the

training plan (e.g., injury and training history, stage of season, microcycle, etc.).

"FACTS" ABOUT WORKLOAD MONITORING – WHAT DOES THE EVIDENCE SAY?

All practitioners involved in the training process (e.g., coaches, physiotherapists, and strength and conditioning staff) are interested in identifying the optimum amount of training to elicit specific performance levels. This training "dose-response" relationship is analogous to pharmacological studies where chemists wish to understand the positive and negative effects of a particular drug. Sport scientists understand that physically hard training is required in order to prepare athletes for the demands of competition, but are also aware that excessive loading can result in increased injury risk.

Early research reported a positive relationship between training load and injury, suggesting that the harder athletes train the more injuries they are likely to sustain (Gabbett, 2004a; Gabbett & Domrow, 2007). Furthermore, greater amounts of high-speed running have been associated with greater lower-body, soft-tissue injury risk (Gabbett & Ullah, 2012), while reductions in training load resulted in fewer injuries and greater improvements in aerobic fitness (Gabbett, 2004b). However, in more recent times, a significant body of evidence has emerged to demonstrate that high chronic training loads may protect athletes against injury (Hulin et al., 2014; 2016a and 2016b; Gabbett, 2016; Soligard et al., 2016; Murray et al., 2016b; Windt et al., 2016). Collectively, these results suggest that training load might best be described as the "vehicle" that drives athletes towards *or away from* injury (Windt & Gabbett, 2016).

In the first study to demonstrate the protective effect of high training loads, Hulin et al. (2014) reported that cricket fast bowlers who bowled a greater number of balls over a four week period (i.e., *chronic training load*) had a lower risk of injury than bowlers who bowled fewer balls. These findings have subsequently been replicated across a wide range of sports (e.g., rugby league, Australian football, Gaelic football) (Hulin et al., 2016a and 2016b; Murray et al., 2016a; Malone et al., 2016a and 2016b). Importantly, the best predictor of injury was the size of the current week's

training load (termed *acute training load*) in relation to the chronic training load. We have termed this the "*acute:chronic workload ratio*" (also previously referred to as "training-stress balance") (Gabbett, 2016). When the acute:chronic workload ratio was within the range of 0.8 to 1.3 (i.e., the acute training load was approximately equal to the chronic training load), the risk of injury was relatively low. However, when the acute:chronic workload ratio ≥1.5 (i.e., the acute training load was much greater than chronic training load), the risk of injury increased exponentially (Figure 9.6) (Blanch & Gabbett, 2016). The protective effect of training appears to arise from two sources: (1) exposure to "load" allows the body to tolerate "load", and (2) training develops the physical qualities (e.g., strength, prolonged high-intensity running ability, and aerobic fitness) that are associated with a reduced injury risk (Gabbett & Domrow, 2005; Gabbett et al., 2012; Malone et al., 2016a). There are several methods available to calculate the acute:chronic workload ratio including the use of rolling averages (Gabbett, 2016), exponentially-weighted moving averages (Murray et al., 2016a; Williams et al., 2016), different acute and chronic loading windows (Carey et al., 2016), and daily calculations. An example of how to calculate the acute:chronic workload ratio on a weekly basis is provided in Table 9.1.

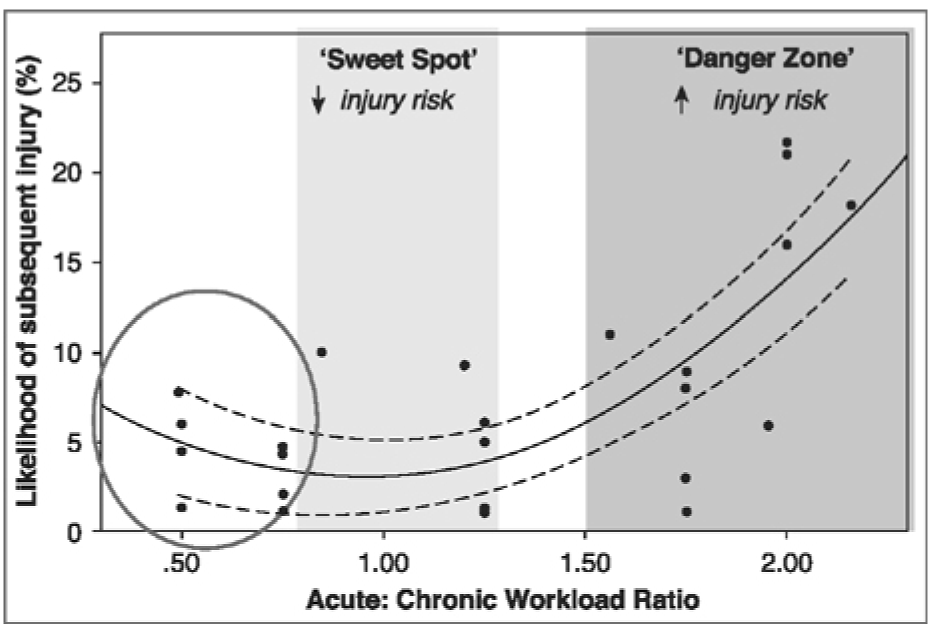

FIGURE 9.6 The acute:chronic workload ratio and likelihood of injury (adapted from Gabbett, 2016). *Although it is simple to recognize that large "spikes" in workload lead to increases in injury risk, it is possible that large "troughs" in workload may also*

increase injury risk. The circled region of the figure highlights injury risk with large reductions in workload. It appears that large "troughs" in workload may also increase injury risk, indicating that both overtraining and undertraining may increase injury risk. There are two possible explanations for this finding: (1) undertraining leaves athletes underprepared for competition demands, and (2) "troughs" in workload generally precede "spikes" in workload.

One final point has been underemphasized within the training load-injury literature. Although "spikes" in training load may contribute to injuries, undertraining and "troughs" in training load may elicit similar negative consequences (see circled area in Figure 9.6). For example, a "U"-shaped relationship between the number of maximal velocity exposures and injury risk has been shown in team sport athletes; both over- *and under-training* increased injury likelihood (Malone et al., 2016b) (Figure 9.7). The risk associated with exposure to maximal velocity running is mitigated through exposure to high chronic training loads (Malone et al., 2016b) (Figure 9.8). Of course, coaches need to be sensible in their approach towards exposing athletes to high velocities. Allowing adequate recovery (at least two days, but more likely three days) following a match and prior to the next match is critical. Equally, the timing of exposures within a session is important to consider. The general consensus is to perform speed training at the beginning of a session and earlier in the training week (following a period of recovery), when athletes are in the most recovered state.

These results have three important practical implications: (1) high chronic training loads may protect against injury, (2) athletes are better able to tolerate the high-intensity components of training if they have been exposed to higher chronic training loads, and (3) the acute:chronic workload ratio is a greater predictor of injury than either acute or chronic load in isolation.

TABLE 9.1 An example of the acute:chronic workload ratio calculation using weekly rolling averages. *Several methods have been proposed to calculate the acute:chronic workload ratio. The reader is encouraged to consult individual studies to evaluate the relative merit of these methods. Note that the variable used to monitor workload will depend on the sport. For example, high-speed running may be important for football players, while the number of pitches thrown may be the important workload variable for a baseball pitcher. For the purpose of this table, total weekly distance (kilometres) has been chosen as the workload variable of interest. A "spike" in workload in week 7 resulted in an acute:chronic workload ratio of 1.35 which may put the athlete at increased risk of injury*

Training Week	*Acute Workload*	*Chronic*	*Acute:Chronic Workload*

		Workload	*Ratio*
Week 1	10 km	–	–
Week 2	12 km	–	–
Week 3	14 km	–	–
Week 4	15 km	12.75 km	1.18
Week 5	14 km	13.75 km	1.02
Week 6	20 km	15.75 km	1.27
Week 7	25 km	18.50 km	1.35
Week 8	22 km	20.25 km	1.09

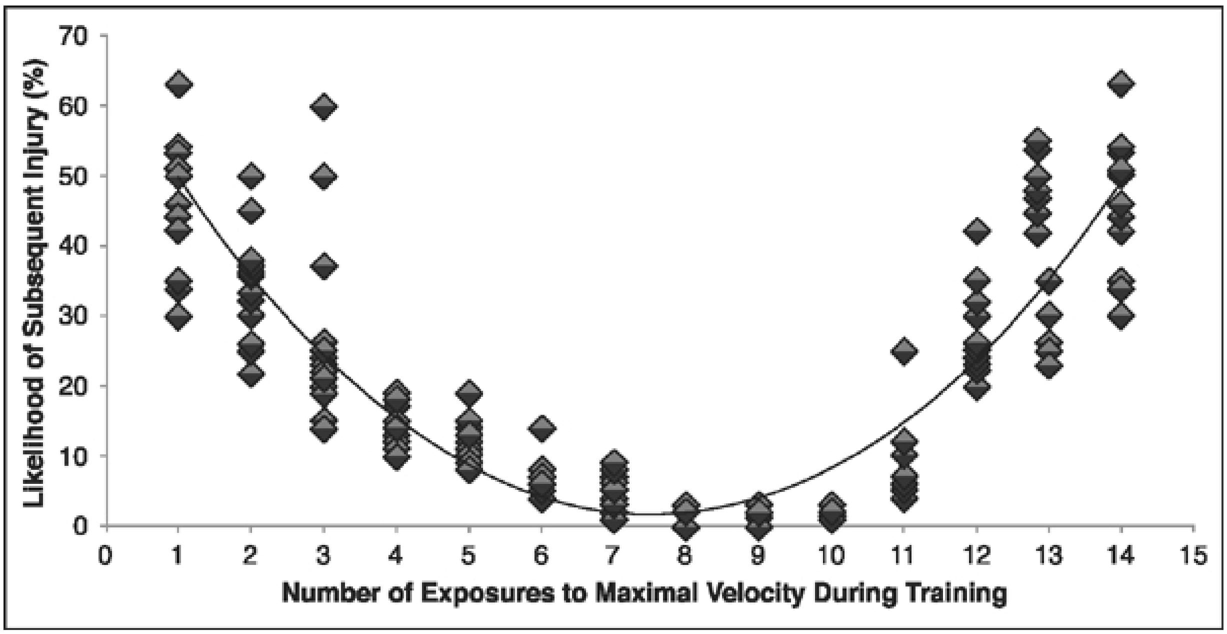

FIGURE 9.7 Relationship between maximal velocity running and likelihood of injury (adapted from Malone et al., 2016b).

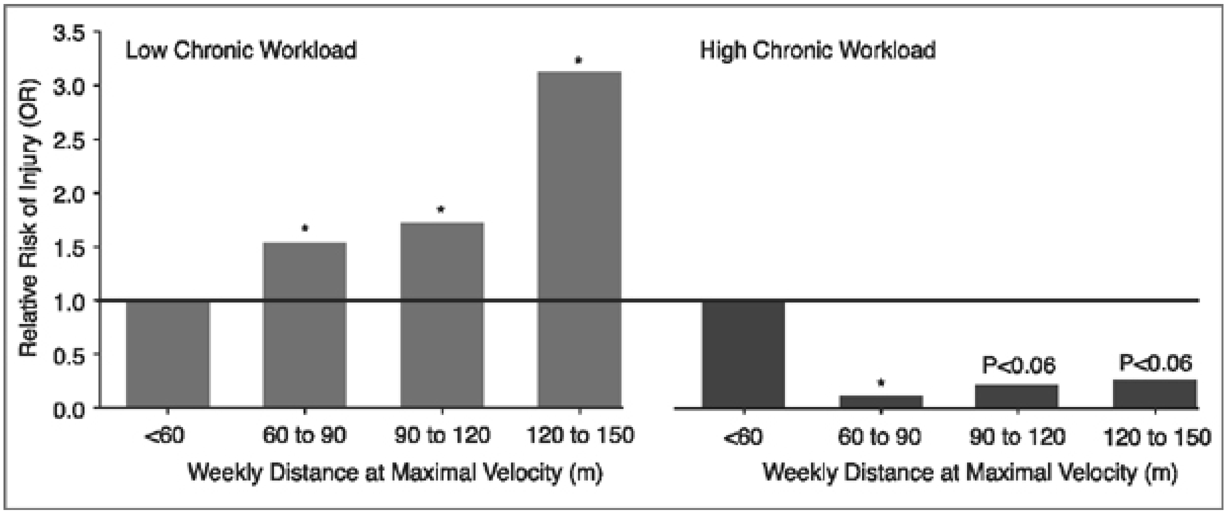

FIGURE 9.8 Combined effect of chronic load history and maximal velocity exposure on injury risk (adapted from Malone et al., 2016b).

SUMMARY

All members of a sport performance team, including coaches, strength and conditioning, and medical staff, are interested in the optimum dose of training required to achieve specific performance levels. On the one hand, too much training may leave the athlete predisposed to excessive fatigue, while too little training may result in the athlete being underprepared for the demands of competition. Until recently, the optimum training load to maximize performance and minimize injury risk has largely been a theoretical concept. For example, despite common belief, it has been shown that high chronic workloads may protect against injury as long as these workloads are achieved safely. Recently, we have presented the acute:chronic workload ratio (i.e., the size of the short-term workload, termed *acute workload*, in relation to the workload performed over a longer period of time, termed *chronic workload*) as a means of safely progressing athlete training programs. Our findings have shown that maintaining an acute:chronic workload ratio between 0.8 and 1.3 (i.e., slight decreases and increases in workload) results in minimal injury risk, whereas large fluctuations (including spikes and troughs) in workload result in large increases in injury risk. Despite these findings, it is important to recognize that coaches (and support staff) are constantly evaluating the risks and rewards of training, and that *injury risk is not identical to injury rate.*

Fluctuations in workload can arise from unplanned (e.g., poor session and weekly planning or intense matches) and also planned (e.g., congested fixture schedules, “shock blocks”) origins; while these spikes and troughs in workload may carry increased risk, when prescribed as part of a well-planned training program they may also elicit performance benefits.

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CHAPTER 10

Priming match-day performance: Strategies for team sports players

Mark Russell, Natalie Williams and Liam P. Kilduff

SECTION 1: LITERATURE REVIEW

Elite sporting competitions typically start at varying times throughout the waking day. In the case of team sports, kick-off can occur anywhere between 11:00 hours (e.g., Academy football games) to 21:00 hours (e.g., elite evening matches). While extraneous factors, including the demands of television (Drust et al., 2005), likely determine these start-times, athletes may be susceptible to changes in physical performance throughout the day (Chtourou and Souissi, 2012, Teo et al., 2011a, Teo et al., 2011b). While an abundance of research has profiled the effects of different preparatory strategies on markers of team sport performance, a potential role also exists for interventions performed on the day of a match to acutely enhance subsequent performance (Kilduff et al., 2013a, Russell et al., 2015b). This chapter provides suggestions for additional and/or modified practices which are likely beneficial for team sports players. Although not mutually exclusive, such strategies can broadly be categorised as those which are implemented: 1) more than three hours before a match commences (e.g., prior priming exercises), 2) less than three hours before competition starts (e.g., modified warm-up practices including post-activation potentiation [PAP] and heat maintenance strategies, ischemic pre-conditioning [IPC] and hormonal priming), and 3) during scheduled within-match breaks (e.g., half-time; heat maintenance strategies).

STRATEGIES IMPLEMENTED MORE THAN THREE HOURS BEFORE A MATCH COMMENCES

Attenuating the effects of sleep deprivation

In agreement with data from the general population (Kronholm et al., 2009), empirical observations highlight that sleep deprivation is common on the night(s) prior to sporting competition, especially if matches require prior international air travel. While the performance effects of acute sleep loss appear equivocal (Blumert et al., 2007, Oliver et al., 2009, Cook et al., 2011) highlights a potential modulating role of sleep duration on skilled performance. Specifically, in a rugby passing task, players who self-

reported seven to nine hours' sleep on the night before testing outperformed their sleep-deprived counterparts (i.e., those reporting three to five hours sleep) by ~20% (Cook et al., 2011). Interestingly, such differences were ameliorated when creatine (50 or 100 mg·kg-1) or caffeine (1 or 5 mg·kg^{-1}) were provided to sleep-deprived players 90 minutes before skill testing commenced, a response attributed to the attenuation of sleep-deprivation induced reductions in brain phospohocreatine concentrations and the stimulatory effects of adenosine-receptors, respectively (Cook et al., 2011). While the morning timing of the skilled assessment must be noted (11:30 hours), provision of a caffeine or creatine dose upon waking may elicit ergogenic effects for activities, including skilled actions, performed thereafter.

Prior priming exercise

Optimised physical performance is subject to a range of both intrinsic and extrinsic factors. Circadian rhythmicity, a roughly 24-hour cycle of physiological and behavioural processes, is acknowledged as one of many modulators of numerous key performance indicators (Atkinson and Reilly, 1996, Chtourou and Souissi, 2012, Teo et al., 2011b). For example, changes in anaerobic physical performance (e.g., force and power expression) occur at different times of the day (Chtourou and Souissi, 2012, Teo et al., 2011a). Offsetting circadian declines in performance may prove beneficial for team sports players.

Testosterone (T) and cortisol (C) have been implicated in the modulation of performance in elite athletes (Cook and Crewther, 2012b), and show circadian rhythmicity with an early morning (A.M.) peak followed by a transient decline through the day (Kraemer et al., 2001, Teo et al., 2011a). Considering the potential role of T in mediating athletic performance and behaviour, offsetting the circadian decline could be of benefit to sporting activities performed at times when circadian declines in T persist, such as in the afternoon (P.M.).

A strength or hypertrophy training stimulus can acutely raise post-exercise concentrations of T (Kraemer and Ratamess, 2005), and thus, in the context of starting an event with elevated T, may be beneficial to precede subsequent competition. Indeed, Ekstrand et al. (2013) have demonstrated that A.M. resistance exercise that included back squats

performed to failure and power clean exercises, improved throwing distance in well trained shot-putters six hours later. Similarly, improved P.M. performance was observed when rugby union players preceded P.M. performance assessments with sprints (5 × 40m) and whole-body resistance (bench press and back squat routines up to 100% of three repetition-maximum (RM) values) exercises six hours beforehand (Cook et al., 2013b). Notably, the A.M. sprint and resistance exercise attenuated a circadian decline in T concentrations when compared to a rested control trial (Cook et al., 2013b). Such findings highlight a potential role for specific modes of A.M. exercise to improve P.M. performance, and that such findings may be modulated by changes in hormone status.

However, acknowledging the practical considerations associated with the pre-competition practices of professional team sport players, the methods of A.M. exercise examined previously (Cook et al., 2013b, Ekstrand et al., 2013) may preclude their use on the day of competition and/or have limited transfer to match-specific performance indicators. Whole body resistance exercises performed to maximal intensity and/or failure, while beneficial to linear sprinting and force expression, are unlikely to be routinely adopted in the pre-competition setting. Accordingly, Russell et al. (2016) compared the efficacy of different methods of A.M. exercise on P.M. performances. Specifically, six 40m sprints (incorporating 180° changes of direction) performed ~5 hours before subsequent exercise improved both sprinting and jumping performance while eliciting the greatest effect on salivary T. Additionally, upper-body resistance exercise augmented sprint performance and elicited more favourable T concentrations, whereas cycle sprints increased countermovement jump performance alone. Such findings highlight a possible role of priming methods that may be better accepted by players and coaches on the day of competition while demonstrating transfer to match-specific performance indicators.

Combining prior priming exercise with IPC

Multiple bouts of skeletal muscle ischemia (induced using a cuff or tourniquet) interspersed with periods of reperfusion to acutely enhance muscle function is known as ischemic pre-conditioning (IPC) (Bailey et al., 2012, Jean-St-Michel et al., 2011). IPC has typically been used in isolation as a passive pre-competition strategy that is administered ~1–2 hours before

competition commences (Bailey et al., 2012, Jean-St-Michel et al., 2011, Lisboa et al., 2016). However, Cook et al. (2014) identified an occlusion-dependent elevation in salivary T immediately following a resistance exercise session that also utilised IPC. This response was achieved using five sets of five repetitions at 70% 1RM – a significantly lower volume of work when compared to previous priming studies (Cook et al., 2013b, Ekstrand et al., 2013). While further research is required, evidence suggests that IPC could be used in combination with resistance exercise as a more favourable and practical pre-competition strategy via attenuation of circadian declines in T.

STRATEGIES IMPLEMENTED LESS THAN THREE HOURS BEFORE A MATCH COMMENCES

Ischemic pre-conditioning

As outlined previously, IPC has typically been used in isolation as a passive pre-competition strategy. Mechanisms to explain the efficacy of this performance-enhancing strategy relate to the increase in muscle blood flow resulting from changes in adenosine concentrations and the function of intra-muscular adenosine triphosphate (ATP)-sensitive potassium channels. Improved oxygen delivery and metabolite clearance via an increase in blood flow potentially up-regulates intra- and extra-cellular movement (de Groot et al., 2010). Increased muscle force contractility (via a more efficient excitation-contraction coupling process) has also been proposed to explain the efficacy of IPC in animals (Pang et al., 1995).

Within the constraints of athletic performance, the benefits of IPC have been observed in time to exhaustion (Crisafulli et al., 2011, de Groot et al., 2010), anaerobic performance (Bailey et al., 2012, Jean-St-Michel et al., 2011, Lisboa et al., 2016) and muscle activation (Wilson et al., 2013b, Yasuda et al., 2014) when implemented as a passive pre-competition strategy. Bailey et al. (2012) reported significant reductions in blood lactate accumulation and a 34 second improvement in 5000m running time when a group of healthy males preceded exercise with 4 × 5 minute bouts of bilateral occlusion at 220 mmHg, followed by 45 minutes of rest. Similarly, 100m swim time-trial performance was improved (~1%; equivalent to 0.7

seconds) 45 minutes after an upper limb IPC protocol which included 4 × 5 minutes of occlusion (cuff inflated to 15 mmHg greater than measured systolic arterial pressure) (Jean-St-Michel et al., 2011). However, not all studies examining the effects of IPC in intermittent sports players have yielded positive results (Gibson et al., 2013).

A time-dependency of IPC efficacy may exist as Lisboa et al. (2016) reported that the ergogenic effects of IPC (4 × 5 minute bouts of occlusion; 220 mmHg and 180 mmHg for thighs and arms, respectively) which were absent when performed within one hour of subsequent exercise manifested after a two or eight hour post-IPC recovery period. Although the application of IPC to intermittent team sports players warrants further investigation, IPC could prove efficacious for use on the day of competition.

Hormonal priming

Concentrations of T are positively correlated to indices of physical performance deemed crucial to team sports performance (e.g., positive correlation between baseline T concentrations and ability to produce power) (Crewther et al., 2012b, Crewther et al., 2009, Cook and Crewther, 2012a, Crewther et al., 2012a). For example, squat strength ($r = 0.92$) and sprint times ($r = –0.87$) are correlated with salivary T in elite strength trained athletes (Crewther et al., 2012a). A potential link also exists between endogenous T and aspects of athletic behaviour related to motivation and confidence to compete (Cook and Crewther, 2012b). Notably, in Judo, free T concentrations have been positively associated with numerous offensive behaviours as well as success in both physical and non-physical tasks (Salvadora et al., 1999).

Key coaching messages delivered in pre-match talks that outline tactical practices (<3 hours prior to competition) and aim to motivate and instil confidence in players through the use of verbal persuasion (<1 hour prior to competition) are usually reinforced through the warm-up and the final 20 minutes before the start of competition. However, the extent to which such practices benefit a player’s performance are unclear. When performed 75 minutes before a match, positive coach feedback which accompanies a player viewing footage of themselves performing a skill successfully has been reported to promote the highest pre-game T concentrations and best performance ratings (Cook and Crewther, 2012b). Conversely, cautionary

coach feedback accompanying videos of successful skill execution by an opposing player produced larger C responses and worse performance ratings. Moreover, presenting highly trained males with aggressive or intense training videos acutely raised T, which was associated with improved 3RM back squat performance 15 minutes later (Cook and Crewther, 2012a). Therefore, watching videos and receiving associated feedback has the potential to influence hormonal and performance responses and might provide a suitable strategy for the preparation of team sports players before competition. In the context of applied practice, it may be worthwhile to include such strategies during the team briefing as these very often include the use of video footage and performance analysis.

Modifying the warm-up: Increased intensity

Transitioning an athlete from a state of rest to a state of exercise, while minimising residual fatigue, is the principal aim of a warm-up. As such, the warm-up intensity is a key consideration for the effectiveness of this pre-competition strategy. Albeit from events outside of the scope of team sports, an athlete's normal warm-up practices may be less than optimal, especially in relation to exercise intensity (Cook et al., 2013a, Ingham et al., 2013). Ingham et al. (2013) reported that modifying prior exercise (300m of striding; 6 × 50m separated by a 45–60 second active recovery) to an equidistant warm-up of 100m of striding (2 × 50m separated by a 45–60 second active recovery) and 200m of race pace running elicited improved 800m time trial performance (~1%). Moreover, increasing the typical warm-up intensity by ~30% improved mean 20m resisted sprint performances in elite bob-skeleton athletes (Cook et al., 2013a). Therefore, it may be worthwhile for practitioners to consider opportunities to increase the intensity of all or isolated drills used in the team-sport warm-up; however, the efficacy of such practices are yet to be confirmed when prolonged (e.g., 45 minutes or longer) as opposed to short (e.g., fewer than ten minutes) durations of competition follow warm-up activities.

Modifying the warm-up: Protection of gains

In the absence of heat-protection interventions, body temperature decreases rapidly following the cessation of exercise (Kilduff et al., 2013b, Mohr et

al., 2004, Sargeant, 1987, West et al., 2013b, Russell et al., 2015a). From an applied context, a player's own preferences (e.g., final kit and tactical preparations), pre-match ceremonies (e.g., meeting with dignitaries, national anthems) and specific rules and regulations (e.g., pitch-protection policies or the use of "call rooms") may result in a 10–20 minute period that separates the end of the warm-up and the start of the match. Temperature losses after similar durations of recovery have been reported to nullify any prior heat gains (Kilduff et al., 2013b, West et al., 2013b, Russell et al., 2015a). Notably, Russell et al. (2015a) observed a loss of 80% of the temperature gained in the warm-up following a 15 minute period of passive rest that preceded a repeated sprint assessment.

Passive heat maintenance, a strategy that typically seeks to maintain muscle and body temperature by attenuation of temperature losses by specialised garments or heating methods, has been proven to be beneficial for minimising post-warm-up reductions in body temperature (Kilduff et al., 2013b, Russell et al., 2015a). Kilduff et al. (2013b) observed that wearing a survival garment during the post-warm-up recovery period offset the core temperature lost by ~50% while also benefitting lower body peak power output and repeated sprint ability in professional rugby league players. Additionally, combining passive heat maintenance with 3 × 5 countermovement jumps (20% body mass load) has been found to elicit further protective effects than heat maintenance alone when used in the post-warm-up period (West et al., 2016). These data demonstrate the importance of maintaining body temperature during the post-warm-up period for offsetting any temperature related decrements in physical performance and thus provide an opportunity for practitioners to improve subsequent performance.

Modifying the warm-up: Post-activation potentiation (PAP)

Force production by a specific muscle group can be influenced by the contractile history of that muscle group (Kilduff et al., 2008). Providing that the mechanisms of muscle potentiation outweigh the residual effects of co-existing fatigue, acute enhancement of skeletal muscle performance has been reported following a pre-load stimulus (Gouvea et al., 2013, Wilson et al., 2013a). Where PAP explains transient improvements in physical performance, mechanisms have been suggested to reflect increased actin-

myosin myofilament sensitivity to Ca2+, enhanced recruitment of motor neurons and/or a more favourable central input to the motor neuron (Tillin and Bishop, 2009, Wilson et al., 2013a). Several factors have been proposed to modulate an athlete's ability to use PAP, such as participant strength, the volume and type of the preload stimulus and the duration of recovery between the preload stimulus and subsequent activity (Wilson et al., 2013a). In the context of modifiable factors that may influence the use of PAP on the day of competition, the literature concerning the volume and type of the preload stimulus are primarily discussed here, although it is acknowledged that other factors such as the strength of the player and the timing of the intervention relative to subsequent exercise modulate the efficacy of PAP interventions.

Hamada et al. (2003) emphasised the importance of preload stimulus volume throughout a fatiguing protocol of isometric maximal voluntary contractions of the knee extensors (16 × 5 seconds each separated by three seconds of rest). Maximal twitches were evoked before the first contraction, during each three second rest period and at intervals during the 5 minute recovery period following the final contraction. Over the first three contractions, a 127% increase from baseline values was gradually realised for twitch peak torque. By the final contraction, twitch peak torque progressively decreased to a value of 32% below baseline. Thus, after initially peaking, the influence of fatigue became more dominant as the volume of contractions increased. Notably, a 32% increase above baseline values in twitch peak torque occurred after 30–120 seconds of recovery from the fatiguing protocol (Hamada et al., 2003). The decay of PAP therefore appears inferior to the decay in fatigue; hence, a net potentiated response was observed during recovery.

The majority of studies examining the PAP phenomenon have employed heavy (75–95% 1RM) resistance exercise as the preload stimulus. Where a single set of heavy isotonic exercise has been performed, improvements in power production are primarily absent (Baker, 2003, Jensen and Ebben, 2003, Brandenburg, 2005, McBride et al., 2005). Consequently, in agreement with Hamada et al. (2003), it appears that when trying to harness the effects of PAP multiple sets of a preload stimulus should be programmed. However, bearing in mind the practical considerations associated with the pre-competition practices of team sport players, the use of heavy resistance exercise is likely not feasible before a game. Alternative

methods of inducing PAP that require less equipment and/or might be better tolerated by players and coaches on the day of competition are therefore appealing.

Ballistic activities such as weighted jumps are associated with the preferential recruitment of type II motor units (Desmedt and Godaux, 1977), and therefore may be utilised as a PAP stimulus. Previous research has also reported that depth jumps are able to increase strength (Masamoto et al., 2003) and high velocity performance (Hilfiker et al., 2007), while the use of isometric maximal voluntary contractions also induce PAP (Guillich and Schmidtbleicher, 1996, Hamada et al., 2003). Turner et al. (2015) observed that three sets of ten repetitions of alternate-leg bounding whilst wearing a weighted vest (incorporating 10% of body mass), improved 10m and 20m sprint performance by 2–3% at four and eight minutes post-bounding. Notably, using 3 × 3 ballistic bench throws at 30% 1RM, West et al. (2013a) reported that improvements in upper body power output occurred after an eight minute recovery period, and that the magnitude of this improvement was similar to that induced by a more traditional heavy resistance exercise bout (i.e., 3 × 3 bench press at 87% 1RM). Therefore, ballistic activities might provide an alternative method of inducing a PAP response that is comparable in magnitude to that induced during heavy resistance exercise, but might be preferable to players and staff on the day of a game.

From a practical perspective, given the transient nature of the PAP response and the timeframe separating the end of the warm-up and the start of competition, the benefit of PAP to subsequent performance could be limited to the initial stages of a player’s involvement in competition. Nevertheless, pooled estimates of change and effect size analyses show that a warm-up based on PAP produces benefits to jump (3.73%, effect size = 0.26) and sprint performances (4.7%, effect size = 0.79) compared with control or other warm-up activities (Hammami et al., 2016). However, it has not yet been determined whether the tactical introduction of substitutes who have induced a PAP response can influence team performance at varying stages of a game, and/or whether PAP has promise as a potential half-time strategy. Likewise, the repeatability of PAP-induction remains to be established in team sports players.

STRATEGIES IMPLEMENTED DURING SCHEDULED WITHIN-MATCH BREAKS (E.G., HALF-TIME)

A 10–20 minute temporary mid-way pause in play, known as half-time, is a common feature of most team sport matches, and typical activities include players returning to the dressing room, engaging in tactical discussion, receiving medical treatment and consuming nutritional ergogenic aids (Russell et al., 2015b, Towlson et al., 2013). However, 20% of soccer players have their least intense 15 minute period of a match within the initial stages of the second half (Mohr et al., 2005), and when compared to the opening 15 minutes of soccer match-play, selected physical performance markers decrease in players and referees between 45 and 60 minues (Lovell et al., 2013a). Therefore, half-time has been proposed as an opportunity to enhance subsequent performance (Russell et al., 2015b). In order to avoid replication of the interventions already discussed, an overview of studies reporting the specific use of half-time interventions now follows. Interested readers should also consider the use of the aforementioned strategies (e.g., PAP, hormonal priming, etc.) to supplement those presented here.

Heat maintenance strategies

During a passive half-time period, muscle and core temperature reduces in excess of 1°C (Mohr et al., 2004), a finding comparable to that reported previously at the end of the warm-up (Kilduff et al., 2013b, West et al., 2013b, West et al., 2016). As protection of temperature-related mechanisms have proven beneficial post warm-up, such strategies may also have efficacy when implemented during the half-time period of matches played in temperate conditions. Accordingly, Russell et al. (2015a) observed attenuated losses of core temperature when professional rugby union players wore survival jackets throughout a 15 minute simulated half-time. Notably, the drop in core temperature over half-time was associated with reductions in peak power output thereafter. While ergogenic effects have been observed, consideration should be given to the logistics of passive heat maintenance strategies in the context of applied practice as some players (e.g., those receiving injury treatments) may find this approach restrictive when additional clothing is worn during half-time. Likewise, the possible deleterious effects that omitting a period of temperature recovery may have

upon performances executed in hot and humid conditions remains to be characterised.

Alternative methods of heat preservation may include short bouts of activity, a strategy known as active heat maintenance, which has demonstrated efficacy over half-time (as reviewed by Hammami et al., 2016). Seven minutes of moderate-intensity running commencing mid-way through half-time has been found to attenuate a 1.5°C reduction in muscle temperature and protect the 2.4% decrements in mean sprint performance observed under control conditions (Mohr et al., 2004). Likewise, Edholm et al. (2014) reported similar magnitudes of sprint performance maintenance and attenuated losses in jump performance following a low-intensity half-time rewarm-up. Additionally, beneficial effects have been yielded from intermittent agility exercise, whole body vibration, small-sided games and lower body resistance exercises performed during half-time (Lovell et al., 2013b, Zois et al., 2013).

Skilled, as well as physical, performances may benefit from active rewarm-ups performed during half-time. For example, seven minutes of low/moderate-intensity activity and light calisthenics performed towards the end of half-time improved performance during an actual match as less defensive high-intensity running, and more ball possession, was observed in the second half (Edholm et al., 2014). Skilled performance during an isolated technical assessment has also been reported to be maintained when small-sided games incorporating skilled actions were performed during a simulated half-time break (Zois et al., 2013). However, while active rewarm-ups appear beneficial, consideration must be given to the duration of the activities performed in the context of applied practice. Likewise, the possibility that additive effects may be elicited from combining methods of active and passive heat maintenance remain to be determined in the half-time as opposed to post-warm-up paradigm (West et al., 2016).

DO PRE-COMPETITION STRATEGIES APPLY TO PRE-TRAINING?

This chapter has so far considered pre-exercise and priming activities for the benefit of subsequent *competitive* performance. While evidence exists to support the influence of prior exercise on key performance indicators

executed thereafter, it remains to be determined if chronic training adaptations can also benefit from such activities. At some point in the season, empirical observations highlight that the majority of team sports require training days that consist of two or more sessions performed within a day.

It could be argued that, either intentionally or unintentionally, the structure of the training day is using prior activity to either 1) influence afternoon performance (and thus the intensity of the adaptive stimulus), or 2) periodise specific components of training in scenarios where competing demands are placed on players. As discussed previously, the benefits of preceding specific activities with a prior exercise session is a desired effect of priming exercises performed up to six hours before (Cook et al., 2013b, Ekstrand et al., 2013, Russell et al., 2016). Moreover, despite neuromuscular, endocrine or physiological responses over a 24 hour follow-up period not being affected by the within-day sequencing of strength and speed training (two hour inter-session recovery), 10m sprint time was enhanced when a speed session was sequenced second (Johnston et al., 2016a). Therefore, the structure of a training day can be manipulated to acutely exaggerate specific session aims, but the chronic training adaptations resulting from the long term cumulative effects of such session structures remains to be determined.

Conversely, interference theory (a phenomenon whereby competing adaptations such as the expression of strength or endurance appear muted in concurrent training programmes) highlights that simultaneous programming of opposing training stimuli may be detrimental to the potential realised if each training stimulus is performed in isolation. Hickson (1980) reported attenuation of strength gains when endurance and strength training were performed concurrently over a ten week period. Likewise, Ratamess et al. (2016) reported 9–19% reductions in resistance exercise performance when 15–45 minutes of endurance exercise was performed ten minutes beforehand. However, Jones et al. (2016) reported a superior ability to maintain a relative strength loading intensity when strength training was performed prior to endurance exercise as opposed to vice versa. Evidence therefore exists concerning the impact of session ordering within a single day.

A further consideration relates to the effects that residual fatigue may have as most periodisation strategies would advocate a transition from high

speed/low force activities (e.g., speed or technical sessions) to high force/low speed actions (e.g., strength training) based upon the degree of complexity (and thus risk of error/failure and injury) a player experiences. Indeed, Jones et al. (2016) reported that post-session blood C and lactate concentrations were greater when endurance training was performed immediately prior to strength training as opposed to vice versa. On the other hand, despite subjective markers of muscle soreness being elevated for 24 hours, Johnston et al. (2016b) report no performance differences between a single (maximal speed session: 6 × 50m sprints, 5 minute intra-set recovery) or double (maximal speed session plus 4 × 5 back squats and Romanian deadlift at 85% 1RM) training day when two hours separated consecutive sessions. Although differences in the recovery time between sessions, and the degree of similarity between the two exercise stimuli examined, may explain the divergent results, practitioners should bear in mind the degree of cumulative fatigue that players experience over the course of the training day. Residual fatigue resulting from a prior training session may compromise movement qualities (and plausibly elevate injury risk) in a subsequent team technical session that is inherently more unpredictable than resistance training. Further research is therefore required to ascertain the effects of priming exercises on chronic training adaptations as opposed to acute competitive performances.

SECTION 2: PRACTICAL APPLICATIONS

In addition to the time spent training and preparing players for competition, match-day also provides an opportunity to enhance subsequent performance (Kilduff et al., 2013a, Russell et al., 2015b). Implementation of appropriate warm-ups, heat maintenance strategies, post-activation potentiation (PAP), ischemic pre-conditioning (IPC), hormonal priming and prior priming exercise has been found to acutely enhance performance thereafter. Given the range of times when most team sport competitions commence (e.g., 11:00–21:00 hours), it may be possible for practitioners to implement a number of these acute interventions in pursuit of additive performance enhancing effects. A theoretical model that incorporates multiple strategies which could contribute to a multifaceted match-day performance enhancement initiative is presented.

In order to further understand the "windows of opportunity" which may exist on match-day, it is important to initially contextualise the current practices of team sport players. A theoretical outline of the *typical* activities performed in the 12 hours before an away match (with overnight hotel stay) with a 20:00 kick-off (0 hour) is presented in Figure 10.1.

Generally, players may be encouraged to sleep in on the morning of a match but may awaken in time for a team breakfast 12 hours before kick-off. Thereafter, players may partake in a bout of low-intensity exercise, such as a walk or jog, which precedes a period of rest and recuperation before lunch is served. After a period of the player's own time, a technical or tactical briefing may then follow before the logistics of travel to the match venue are undertaken. Within two hours of kick-off, players have arrived at the match venue and the preparations that follow might then become more individualised to a player's needs and focus upon the organisation of playing kit, self-motivation strategies, one-to-one player/coach interactions and provision of *ad hoc* medical/physiotherapy attention. A team-based pre-match warm-up will then be undertaken and hydro-nutritional strategies that seek to optimise a player's preparedness for subsequent exercise will continue during this period.

As the match-day practices of professional sports teams are very often structured and rigid in nature, it is imperative that any proposed modification to the preparatory period seeks to complement existing

protocols. Accordingly, practical guidelines to incorporate such strategies may therefore be beneficial for practitioners. A theoretical model of organising the pre-match period to supplement the practices currently employed with the performance enhancing strategies outlined previously in the chapter is presented in Figure 10.2.

Strategies which practitioners may wish to consider can broadly be categorised as those which are administered before competition commences and those which can be implemented during scheduled breaks in play. If the night preceding competition has yielded poor sleep quality and/or duration, then ingestion of acute doses of caffeine (up to 5 mg•kg-1) or creatine (up to 100 mg•kg-1) may help to attenuate the negative effects of sleep-deprivation (Cook et al., 2011). Based on previous evidence relating to physical performance, a priming exercise session performed five to six hours before a match commences could offer an effective strategy for optimised match performances (Cook et al., 2013b, Russell et al., 2016, Ekstrand et al., 2013). A 20 minute resistance session that incorporates upper and lower body lifts of varying intensities (three sets at 50, 70, 90 and 100% of 3RM separated by 1.5 minutes of recovery) has been found to be a time efficient performance-enhancing strategy (Cook et al., 2013b, Ekstrand et al., 2013). Likewise, six sets of 40m maximal sprints (20 seconds intra-set recovery) have been reported to attenuate circadian declines in testosterone (T) and improve subsequent jump and sprinting performances (Russell et al., 2016). Combining ischemic preconditioning (IPC) with resistance exercise may also afford benefits while concomitantly reducing the overall load required in this session (Cook et al., 2014). Performing a priming session before travelling to the match venue might offer a practical method of implementing this strategy (Figure 10.2).

Positive cues from a coach that accompany individualised footage of successful player executions might also benefit performance (Cook and Crewther, 2012b, Cook and Crewther, 2012a). Of cautionary note however, if such videos focus upon the successful skill executions of opposing players, an enhanced stress response may be observed (Cook and Crewther, 2012b). Considering that team briefings that take place before travel to the match venue often include the use of video footage, modification of the team briefing to include hormonal priming activities may offer a logistically feasible method of incorporating such a strategy on match-day.

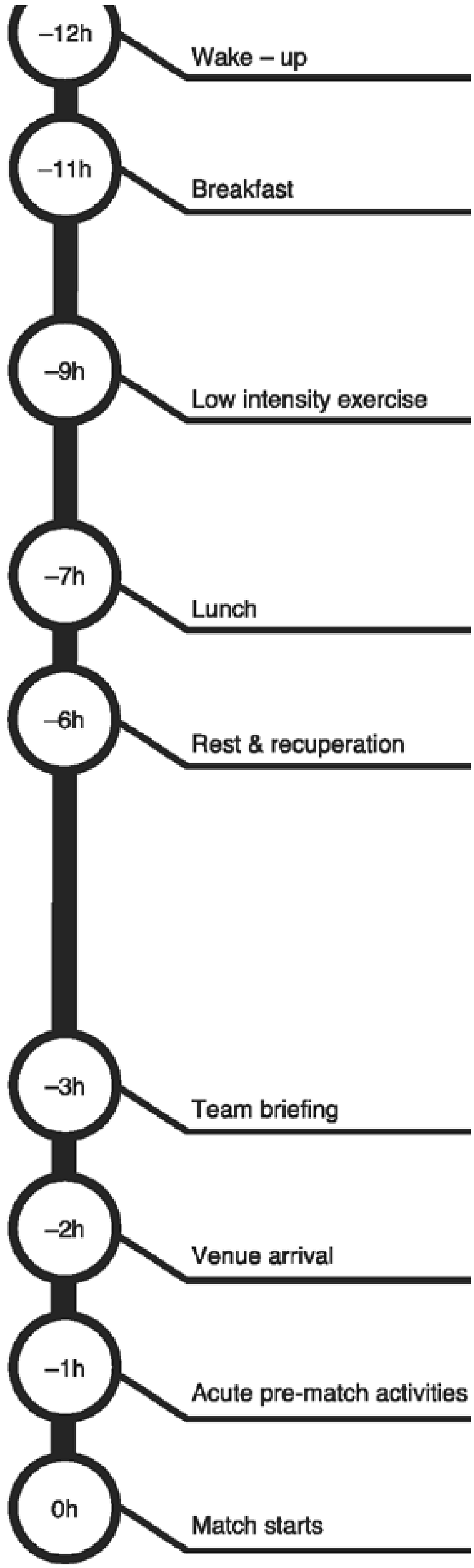
–12h
Wake – up
–11h
Breakfast
–9h
Low intensity exercise
–7h
Lunch
–6h
Rest & recuperation
–3h
Team briefing
–2h
Venue arrival
–1h
Acute pre-match activities
0h
Match starts

FIGURE 10.1 A theoretical outline of the *typical* activities performed in the 12 hours before an away match (with overnight hotel stay) with a 20:00 hour kick-off (0 hour).

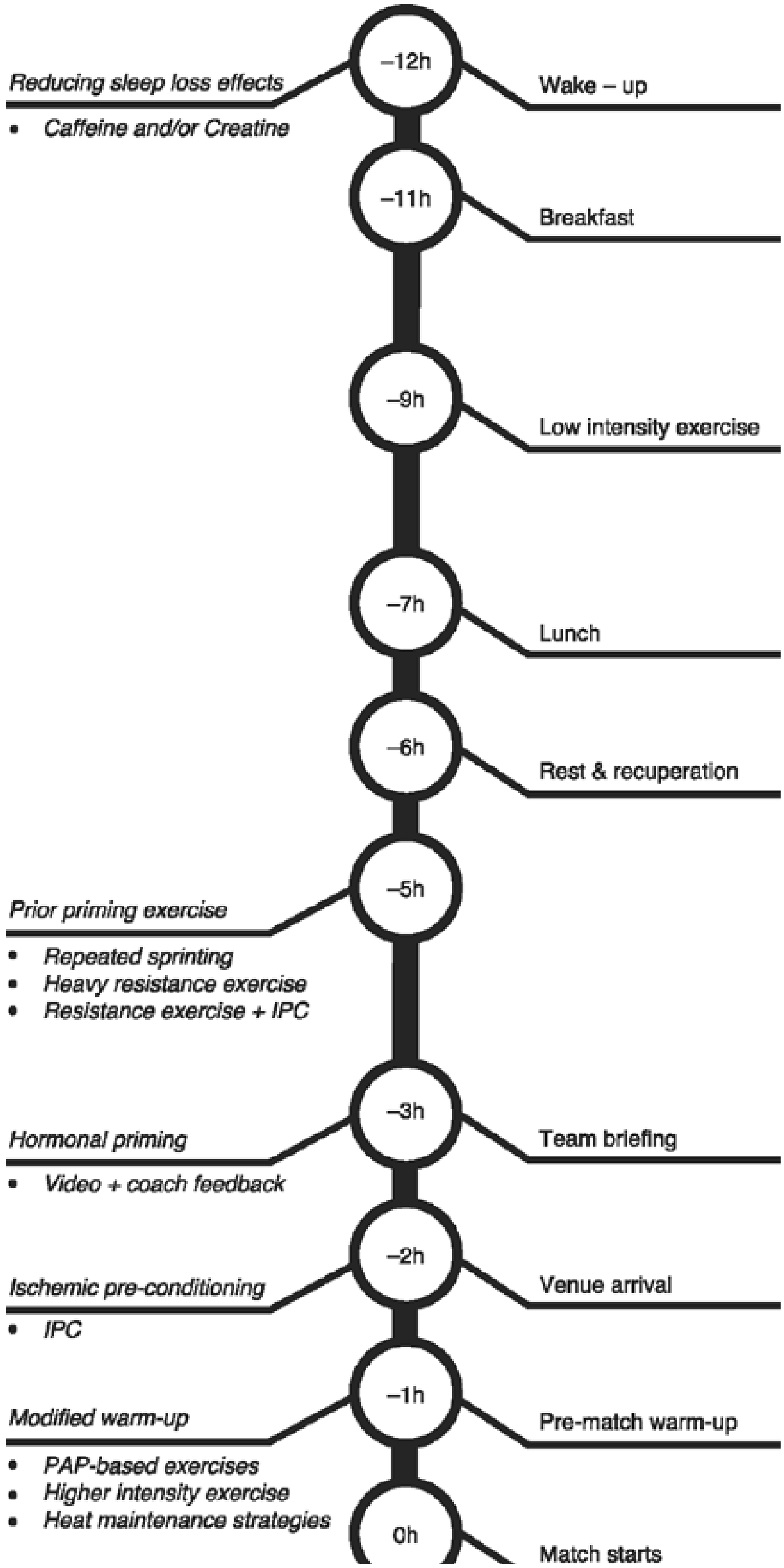

FIGURE 10.2 A theoretical model of organising the pre-match period to supplement the practices currently employed with the performance enhancing strategies outlined in the chapter.

Within 45 and 120 minutes of subsequent exercise, isolated bouts of IPC may be worthwhile (Bailey et al., 2012, Jean-St-Michel et al., 2011, Lisboa et al., 2016), perhaps by alternating bouts of ischemia (induced through the use of a cuff or tourniquet) and reperfusion either before the warm-up or by modifying warm-up content to include such a strategy. Similarly, the warm-up could be further modified in relation to its intensity of specific or all drills performed as "normal" warm-up practices are usually less than optimal (Cook et al., 2013a).

Where possible, fewer than 20 minutes should separate the end of the warm-up and the start of the match. Additionally, heated clothing, outdoor survival jackets and/or heating pads can be worn over specific musculature to minimise muscle temperature losses in the time separating the end of the warm-up and onset of competition (Kilduff et al., 2013b, West et al., 2016), an approach that might be combined with acute exercise (West et al., 2016) and prove especially worthwhile when players are expected to experience prolonged delays before the start of subsequent exercise (e.g., observing national anthems, waiting to be substituted onto the game and/or between halves of play at half-time).

Attenuating heat losses via additional exercise performed throughout the breaks separating consecutive movement periods may also prove beneficial prior to pitch entry (West et al., 2016). Plausibly, potentiating activities, such as heavy (>75% 1RM) resistance exercise (Gouvea et al., 2013) or ballistic activities (e.g., weighted bounds at body mass + 10% and ballistic bench throws at 30% 1RM) that induce a PAP response (West et al., 2013a, Turner et al., 2015) may concomittanlty attenuate temperature losses occuring in the post warm-up period while also benefitting subsequent explosive actions. Consideration would need to be given to the practical application here, but as ballistic exercises elicit comparable results to traditional heavy resistance exercise (West et al., 2013a), ballistic exercises might provide a practical method of inducing PAP and improving subsequent performance during match-play when a suitable recovery time is

implemented (i.e., between 4–12 minutes). Likewise, while accounting for current half-time practices (Towlson et al., 2013), passive (Russell et al., 2015a) and/or active (Edholm et al., 2014, Lovell et al., 2013b, Mohr et al., 2004) heat maintenance strategies that can be feasibly implemented throughout scheduled breaks in play should be incorporated.

SUMMARY

The support of previous authors for the use of prior priming activities, a well-structured warm-up and half-time interventions means that a method which combines a number of these strategies for use on the day of competition might be of interest to strength and conditioning coaches involved with team sports. A practical model that allows for the combination of a number of interventions which, individually, have been found to enhance the performance of actions involved in team sport match-play, could theoretically elicit additive effects over the use of such strategies in isolation.

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CHAPTER 11

Strategies to enhance athlete recovery

Emma Cockburn and Phill Bell

INTRODUCTION

Reductions in performance potential in the days following strenuous exercise due to insufficient recovery provides a problem for athletes and practitioners alike, particularly given many sporting scenarios require multiple and consecutive day's performance. Consequently, in order to enhance athlete recovery (i.e., physical performance potential), numerous strategies aimed at attenuating physiological stress responses and accelerating return to physiological baseline have been proposed.

Physiological stress responses to strenuous exercise may be muscular or systemic in nature, and are commonly assessed via indices of muscle damage, inflammation or oxidative stress. The stress responses tend to be classified into two categories: the primary phase, which is characterised by direct damage to the muscle and the secondary phase, which involves exacerbation of the damage. Such stress responses may be transient in nature, however, they may have a lengthier impact in respect of their effect on physical performance capacity. Furthermore, there are distinct differences in stress responses which are directly related to the exercise completed, and as such it is important to understand the impact of the type of exercise on the resulting physiological response. In respect of this, dependent upon the activity completed, exercise tasks may be classified into mechanical, metabolic or mixed stress activities. Mechanical stress is most

apparent during high-force eccentric muscle actions, whereas metabolic stress is often the result of prolonged high-energy turnover akin to endurance exercise. These disturbances are characterised in the literature via numerous avenues including but not limited to; elevations in systemically measured molecules, perceptions of pain and, perhaps most importantly in the context of this book, compromised muscular function. It is these responses that recovery interventions aim to influence, with the goal of accelerating performance potential back towards baseline levels.

This chapter aims to explore the application and efficacy of a range of popular and emerging recovery strategies, whilst also providing insight into the physiological mechanisms that underpin the stress response to exercise. Additionally, guidance with regards to real world application of recovery strategies is provided.

SECTION 1: LITERATURE REVIEW

Acute carbohydrate/protein supplementation

Numerous researchers have investigated the effects of nutritional supplements on acute recovery from strenuous exercise (Bell et al., 2016, Cockburn et al., 2013, Howatson et al., 2012, Rankin et al., 2015), and primarily their ability to limit decrements and/or enhance recovery of muscle function. The nutritional supplements investigated are varied and have included creatine (McKinnon et al., 2012), functional foods such as cherry juice (Bell et al., 2016) and blueberries (McLeay et al., 2012) (reviewed in later sections), leucine (Kirby et al., 2012), branched chain amino acids (Howatson et al., 2012) and whey protein (Buckley et al., 2010). Protein supplements are particularly popular due to the belief that they increase muscle mass, improve performance and enhance recovery (Lieberman et al., 2010).

The ingestion of protein or amino acids leads to the stimulation of muscle protein synthesis, which manifests as a positive net muscle protein balance following resistance exercise (Borsheim et al., 2002, Tipton et al., 1999, Tipton et al., 2003). It is hypothesised that due to this change, secondary damage to the muscle will be limited and recovery of muscle function optimised.

Numerous studies have investigated the role of protein supplements on recovery from strenuous exercise with equivocal findings (Betts et al., 2009, Cockburn et al., 2013, Saunders et al., 2007, White et al., 2008, Wojcik et al., 2001). Recently, a systematic review on this topic concluded that the ingestion of protein supplements does not result in reduced muscle damage or enhanced recovery of muscle function (Pasiakos et al., 2014). However, it is well acknowledged that large variability in study design likely contributes to the observed differences. One of these is linked to the variety of protein supplements available, therefore, the remainder of this section will focus on the co-ingestion of protein with carbohydrate (CHO).

Previous research has demonstrated the attenuation of muscle damage with CHO-protein supplements when compared to CHO or placebo solutions (Baty et al., 2007, Cade et al., 1991, Saunders et al., 2004, Saunders et al., 2007, Seifert et al., 2005). However, intramuscular proteins,

specifically creatine kinase (CK) were the only measurement outcomes in all but one study; Baty et al., (2007) demonstrated a reduction in soreness at 24 hours with CHO-protein ingestion. However, basing conclusions predominantly on measures of intramuscular proteins in the blood is problematic for a number of reasons. Firstly, the time course of changes in muscle strength, muscle soreness and blood CK are varied (Peake et al., 2017a), and thus limiting increases in CK may not be extrapolated to attenuating decrements in muscle function. Secondly, CK measured in the blood is not reflective of the magnitude of damage, as CK concentrations also reflect clearance by the reticuloendothelial system (Clarkson et al., 1992). Therefore, it is imperative that when determining the efficacy of recovery interventions, measures of muscle function are included.

Work by Wojcik et al., (2001) found no beneficial effect of a milk-based CHO-protein drink on changes in muscle soreness, isometric peak torque and CK in comparison to both a CHO and placebo beverage. This was despite evidence of damage and increased muscle protein breakdown, findings which were subsequently supported (Betts et al., 2009, Breen et al., 2010, Green et al., 2008, White et al., 2008). The mode of exercise used to elicit a stress response differs substantially (eccentric muscle actions, downhill running, Loughborough Intermittent Shuttle Test); thus, the physiological responses, time course and magnitude of change in muscle function, muscle soreness and intramuscular proteins is likely to differ.

We have repeatedly demonstrated positive effects of CHO-protein supplementation (cow's milk) on recovery of muscle function following a bout of eccentric actions of the knee flexors (Cockburn et al., 2008, Cockburn et al., 2010, Cockburn et al., 2012, Cockburn et al., 2013). Positive effects were also demonstrated for limiting increases in soreness (Cockburn et al., 2010) and intramuscular proteins (Cockburn et al., 2008, Cockburn et al., 2010, Cockburn et al., 2012). Although the mechanistic basis underpinning this effect was not elucidated in this work, it is postulated that the consumption of milk led to a positive protein balance limiting damage to the muscle and/or enhancing repair. Indeed Elliot et al., (2006) demonstrated net muscle protein synthesis following one-legged resistance exercise with the ingestion of milk.

There is clear discrepancy between the findings of Cockburn et al., (2008, 2010, 2012) who found positive effects, and the findings of Green et al., (2008), Betts et al., (2009), Breen et al., (2010), White et al., (2008) and

Wojcik et al., (2001) who demonstrated no effect of CHO-protein supplements on recovery. Although Green et al., (2008), Betts et al., (2009) and Breen et al., (2010) used running or cycling protocols that may explain these contrasting findings, Wojcik et al., (2001) and White et al., (2008) both used eccentric actions, which is similar to Cockburn et al., (2008). One hypothesised explanation may be related to the magnitude of stress response. Both Wojcik et al., (2001) and White et al., (2008) used eccentric actions of the knee extensors in contrast to eccentric actions of the knee flexors, which may be more susceptible to damage. However, White et al., (2008) utilised eccentric muscle actions and demonstrated similar decrements in maximum voluntary isometric contraction to Cockburn et al., (2008), yet did not observe a benefit of CHO-protein supplementation. Therefore, mode of exercise and severity of damage may only explain part of the equivocal findings.

It is more likely that a range of differences in study design contribute to the inconsistent findings. For example, the functional outcomes used (isometric versus isokinetic), the amount, type and timing of CHO-protein supplementation and the training status of participants may all influence the results. For example, both White et al., (2008) and Wojcik et al., (2001) utilised sedentary males; White et al., (2008) provided whey protein; Wojcik et al., (2001) had participants complete cycling exercise 12 hours prior to the bout of eccentric exercise. This is in contrast to Cockburn et al., (2008) who recruited male team sport players and provided milk-based protein which contains both casein and whey. These factors potentially explain the contrasting findings.

It is clear the results are conflicting, but one of the main limitations of research investigating this topic is the reliance on male participants. Evidence from animal studies suggest that oestrogen may limit some of the effects of muscle damage (Stupka and Tiidus, 2001, Komulainen et al., 1999). However, studies in humans are inconclusive. For example, research has found higher levels of soreness in males (Dannecker et al., 2012, Kerksick et al., 2008) with others reporting no gender differences (Dannecker et al., 2008, Sewright et al., 2008). Given this conflicting evidence and the potential for inter-sex variability, results from studies utilising male participants alone cannot be directly applied to females. To date, there are only two studies that have investigated the effect of CHO-protein supplements on acute recovery in females.

Most recently, Rankin et al., (2015) demonstrated that the consumption of CHO-protein (cow's milk) limited decrements in muscle function, increases in soreness and elevations in intramuscular proteins following resistance based eccentric exercise in females. This is in contrast to Green et al., (2008) who utilised a downhill running protocol and provided protein in the form of whey, and found no positive effect of CHO-protein supplementation. Rankin et al., (2015) also studied the effect on males and found that although there were benefits of CHO-protein for attenuating increases in soreness and intramuscular proteins, the same effect was not found for muscle function. This is in contrast to similar research (Cockburn et al., 2008, Cockburn et al., 2010, Cockburn et al., 2012, Cockburn et al., 2013), and demonstrates a different impact of the same supplement in males and females, supporting the point that findings from one sex should not be directly applied to the other.

In summary, no definitive conclusion can be made on the efficacy of CHO-protein supplements for enhancing recovery. This is likely due to the variety of study designs and methods utilised. However, it is unlikely that there are any harmful consequences of this recovery intervention as athletes are recommended to consume both CHO and protein to aid in muscle adaptation.

Antioxidants and functional foods

The use of antioxidant supplements (AO) or functional foods as modalities to enhance exercise recovery has received attention in recent years (Bell et al., 2013). Primarily, vitamin C (Bryer and Goldfarb, 2006, Connolly et al., 2006a, Thompson et al., 2003, Close et al., 2006) and vitamin E (Avery et al., 2003, Beaton et al., 2002, Warren et al., 1992) have been investigated within the literature as AO candidates for accelerating recovery (McGinley et al., 2009). Within the functional food and recovery space, cherries (Bell et al., 2016, Bowtell et al., 2011), blueberries (McAnulty et al., 2011), beetroot (Clifford et al., 2016) and pomegranates (Trombold et al., 2011) amongst others have received varying degrees of attention due to their high volumes of antioxidant compounds.

The rationale underpinning the use of AO or functional foods to accelerate or enhance recovery relates to the purported negative effects of exercise-induced oxidative stress. It has been proposed that due to increased

flux of oxygen through mitochondria during exercise, there is an increased generation of reactive oxygen species (ROS) which subsequently overwhelm endogenous antioxidant defences (Mastaloudis et al., 2004). Following this, a cascade of oxidative damage and inflammation may ultimately result in reduced function of cellular constituents (Powers and Jackson, 2008) and therefore reduced capacity to perform. It follows that supplementing with exogenous AO may complement endogenous AO defences and reduce the purported negative impact of excess ROS. Despite this, however, there is little evidence to support the use of AO supplementation in accelerating functional recovery, although the use of certain functional foods has provided more promising results. As a result, it is important that AO and functional foods are not considered synonymously when referring to modalities to enhance exercise recovery and as such will be considered independently within this section.

The literature investigating the use of AO as a recovery aid has primarily focussed upon exercise-induced muscle damage (McGinley et al., 2009, Goldfarb, 1999, Petersen et al., 2001, Dekkers et al., 1996, Childs et al., 2001, Kaminski and Boal, 1992, Jakeman and Maxwell, 1993) or endurance exercise models (Mastaloudis et al., 2006, Mastaloudis et al., 2004). Additionally, there is a smaller volume of literature reporting antioxidant supplementation effects in response to repeat sprint exercise (Thompson et al., 2003, Thompson et al., 2001a, Thompson et al., 2001b).

Early work suggested that vitamin C supplementation exerted a protective effect against eccentric exercise-induced muscle damage (EIMD) (Kaminski and Boal, 1992). Using a randomised cross-over design, the authors reported that when subjects were supplemented with 1000mg vitamin C (3x per day, three days pre- and seven days post-exercise), lower reports of post-exercise muscle soreness were provided (versus a placebo). Supporting this finding, Jakeman and Maxwell (1993) reported significantly improved recovery of maximal voluntary contraction (MVC) in a group supplemented with 400mg of vitamin C for twenty-one days prior to and seven days following a box-jump based EIMD protocol. Further support is provided by Bryer and Goldfarb (2006) who reported attenuated increases in a number of indices of EIMD following two weeks of pre- and four days of post-eccentric exercise vitamin C supplementation. Providing evidence that vitamin C supplementation may be able to offset the effects of EIMD.

In contrast, a number of studies have found little or no effect of AO supplementation on recovery from bouts of EIMD. For example, Childs et al., (2001) reported no benefit of seven days combined vitamin E/N-acetylcysteine (NAC) supplement in recovery from eccentrically induced damage of the elbow flexors. To the contrary, a number of blood biomarkers related to muscle damage (creatine kinase, myoglobin and lactate dehydrogenase) were reported to be increased, as well as significant increases in a number of oxidative stress indices. Cumulatively, the authors surmised that the antioxidant supplementation had actually increased tissue damage rather than accelerated its recovery. Close et al., (2006) provided further evidence of potential negative effects of AO supplementation on recovery. Specifically, recovery of quadriceps muscle function (isokinetic dynamometry) was delayed in subjects supplemented with 1000mg of vitamin C for two hours prior to and fourteen days following a downhill running protocol used to elicit EIMD. Additionally, there was no difference in DOMS ratings between subjects receiving vitamin C and placebo. Interestingly in this study, the authors reported that oxidative stress was attenuated in the vitamin C group without any corresponding functional benefit, alluding to the possibility that attenuation of oxidative stress was not a mechanism for accelerating functional recovery.

With regards to endurance performance, combined vitamin C and E supplementation (three weeks pre-, six days post-race of 1g vitamin C and 300mg vitamin E) has been shown to reduce markers of oxidative stress in ultramarathon runners, however it did not influence inflammatory indices (Mastaloudis et al., 2004). The same authors reported in a later paper, again using ultramarathon runners, that vitamin C and E supplementation was unable to reduce the effects of post-exercise muscle damage (Mastaloudis et al., 2006). Blood based biomarkers of muscle damage and inflammation were unchanged with vitamin C and E, and recovery of lower limb peak torque was similarly unaffected by supplementation despite increases in plasma vitamin C and E (suggesting good bioavailability).

Cumulatively, the weight of evidence does not support the use AO in accelerating functional recovery, however there does appear to be a degree of efficacy in AO supplementation for reducing the initial stress response (oxidative stress). Notably, however, concerns have been raised in respect of dampening the oxidative stress response during training programmes. In respect of vitamin C & E supplementation, a review has suggested that high

doses may indeed blunt favourable cell signalling processes leading to adaptations, although evidence for direct inhibition of exercise-induced ROS is lacking (Cobley et al., 2015).

Functional foods such as cherries, blueberries, beetroot and pomegranates have received growing attention in the literature with regards to their use as a supplement to aid in recovery. High levels of naturally occurring compounds found within these foods, called anthocyanins, have been shown to exhibit antioxidative and anti-inflammatory properties (Wang et al., 1997, Wang et al., 1999, Seeram et al., 2001, Bitsch et al., 2004) and as such have been proposed to aid in recovery.

Perhaps the most prominent functional food in this category are cherries, which have been demonstrated to accelerate recovery in a number of studies, both in terms of functional performance and related physiological markers. Cherries are notably high in anthocyanins (Bell et al., 2013) when compared to other natural food sources, and as such provide a candidate to impact upon exercise-induced oxidative stress and inflammation.

In the first study to investigate the application of cherry supplementation in a damaging exercise model, Connolly et al., (2006b) reported that supplementation of a Montmorency tart cherry juice mix, four days prior to and four days following an elbow flexor EIMD protocol, protected against maximal isometric strength loss. This finding was further supported by Bowtell et al., (2011) who demonstrated recovery of isokinetic knee extensor force was faster when supplementing with a tart Montmorency cherry juice concentrate (vs. isoenergetic placebo) prior to and following EIMD of the quadriceps.

Positive effects of cherries on recovery have been further demonstrated when using mixed models of inducing post-exercise stress (i.e., eccentric muscle damage and metabolic stress [via prolonged high-energy turnover]) or metabolic stress alone. Accelerated recovery of MVC, 20 metre sprint and countermovement jump performance (mirrored by attenuations in some inflammatory indices), were found in subjects who consumed Montmorency tart cherry concentrate (30 mL, 2x per day) for four days prior to and four days following simulated soccer play (Bell et al., 2016). In another study, participants given Montmorency tart cherry concentrate supplementation for five days prior to and two days following a marathon demonstrated improvements in isokinetic strength recovery and lower values of inflammatory and oxidative stress indices measured in the blood

(Howatson et al., 2010). Although not investigating functional performance, the same group also demonstrated attenuated inflammatory and oxidative stress responses in cyclists completing three consecutive days of simulated road cycling (Bell et al., 2014).

The mechanism underpinning the positive effects on exercise recovery of cherries and other functional foods is not clear. The dampening of the oxidative stress response through direct actions of exogenous functional food antioxidants such as anthocyanins appears unlikely given their poor bioavailability (Bell et al., 2013, Manach et al., 2005). Although a comprehensive review is outside the scope of this section, it has been suggested that functional food based anthocyanins may be able to upregulate the endogenous antioxidant response (Shih et al., 2007, Traustadottir et al., 2009), combatting the function-impairing stress responses associated with strenuous exercise. Whatever the mechanism, there does appear to be a degree of efficacy in the use of functional foods such as cherries in accelerating recovery from exercise.

In summary, the use of AO and functional foods as supplements to aid recovery has received a great deal of attention in the past two decades. Evidence providing efficacy for AO supplements to benefit recovery of functional performance is lacking, however there is a suggestion they do combat oxidative stress. With regards to functional foods, the evidence appears to support the use of foods high in anthocyanin compounds in accelerating recovery. Not covered in detail within this section is the effect of such supplementation on physiological adaptation. However, to date there is no evidence that any naturally occurring functional food inhibits adaptation to training, whereas AO supplementation has been implicated in such undesirable effects (Cobley et al., 2015). Regardless, there are numerous scenarios where recovery is of paramount importance (e.g., within a tournament scenario) and adaptation is not, in which case the use of any recovery strategy that doesn’t hinder subsequent performance may be of value despite a lack of conclusive evidence.

Cold water immersion

Cryotherapy has been extensively used as a recovery intervention. Cold water immersion (CWI) is a popular method of recovery, and as such, this section will focus on research surrounding the use of CWI only.

Traditionally, CWI involves immersion in cold water of less than 15°C, with immersion depth and time varying (waist to shoulder; 3–20 minutes).

A vast number of studies have been conducted on the efficacy of CWI for attenuating decrements in muscle function and increases in soreness (Ingram et al., 2009, Leeder et al., 2015, Roberts et al., 2014). There are varied results, which is likely due to a variety in the mode of exercise, the method of application of CWI (immersion depth; time; temperature), participant training status and outcome measures utilised. A number of meta-analysis studies have been conducted in an attempt to provide general conclusions. Leeder et al. (2012) conducted a meta-analysis on the effect of CWI on recovery from eccentric and high-intensity exercise (drop jumps, simulated team sport, cycling sprints). It was concluded that CWI is an effective strategy for reducing muscle soreness up to 96 hours and has small but significant effects in reducing CK, however the effects on muscle function are unclear (Leeder et al., 2012). Although CWI was not effective for improving the rate of recovery of muscle strength, it was beneficial for recovery of muscle power at 24, 48 and 72 hours post exercise. The authors stated there is no obvious explanation for improvements in muscle power but not strength, although they did speculate that CWI aids in the recovery of type II fibres which are preferentially damaged following eccentric exercise. Type II fibres are predominantly used in high-velocity muscle actions and thus their enhanced recovery would impact on the recovery of muscle power.

Further support for the use of CWI in alleviating muscle soreness at 24, 48 and 96 hours is provided by Bleakley et al., (2012) and Hohenauer et al., (2015). However, there were no clear effects on objective recovery variables (muscle function, muscle damage, inflammation). In contrast to these findings, Higgins et al., (2016) concluded that CWI did not enhance perceptions of muscle soreness in well-trained team-sport athletes following an exercise stress specific to team sports. However, via the meta-analysis they demonstrated that CWI enhanced athletes’ perceptions of fatigue and recovery up to 72 hours post exercise, and was beneficial for attenuating decrements in neuromuscular function (CMJ, max sprints) up to 24 hours post only.

Overall, there is significant variability in the effectiveness of CWI on the recovery of muscle function/performance, but more widespread agreement that it is an effective strategy for reducing muscle soreness. Machado et al.,

(2016) conducted a meta-analysis on the effect of CWI on muscle soreness in an attempt to determine the most effective water temperature and immersion time. Their findings were in support of Leeder et al., (2012), Bleakley et al., (2012) and Hohenauer et al., (2015) in that CWI was more effective than passive recovery for alleviating muscle soreness. Additionally, they concluded that water temperatures of 11–15°C for 11–15 minutes provided the optimal results.

The underlying mechanisms for enhanced recovery of muscle soreness via CWI are related to localised cooling, hydrostatic pressures, the redistribution of blood flow (Ihsan et al., 2016) and analgesic effects. Cold-induced vasoconstriction and hydrostatic pressure increase central venous pressure that facilitates the movement of fluids from intracellular and interstitial spaces to intravascular compartments (Ihsan et al., 2016). The result is an increase in intracellular-intravascular osmotic gradients that aid in the clearance of cellular debris and necrotic tissue (Ihsan et al., 2016). Subsequently, there is a reduction in oedema and inflammation that may limit secondary damage to the muscle and thus attenuate muscle soreness and decrements in muscle function. Both hydrostatic pressure and cold temperatures have been proposed to stimulate these physiological changes. In an attempt to differentiate between the processes, Leeder et al., (2015) compared seated versus standing CWI on recovery following intermittent sprint exercise. No differences were observed in measures of muscle function, soreness, CK and inflammation, suggesting that by increasing hydrostatic pressure via standing there is no additional recovery benefit (Leeder et al., 2015). However, both CWI groups did not improve recovery in comparison to a control. More recently, Higgins et al., (2016) concluded that CWI is more beneficial for recovery of muscle soreness in comparison to thermoneutral water immersion (TWI). This suggests that any underlying mechanisms associated with enhancing perceptions of muscle soreness are associated with temperature rather than hydrostatic pressure.

Although there is limited evidence to distinguish the physiological effects of CWI, the traditional notion is that CWI restricts inflammation and cellular stress. Recently, Peake et al., (2017b) demonstrated that following resistance exercise, CWI did not alter the inflammatory response in comparison to active recovery in physically active men. This was despite the exercise bout stimulating intramuscular inflammation as evidenced by increased numbers of neutrophils and macrophages, and increased

intramuscular gene expression of cytokines. This research provides evidence against the traditional notion that CWI restricts inflammation and cellular stress following resistance exercise (Peake et al., 2017b). Further research is required to elucidate the mechanisms underlying potential enhanced recovery with CWI as the physiological benefits remain unclear.

EMERGING THERAPIES

Whole body cryotherapy

Whole body cryotherapy (WBC) is becomingly increasingly used in sports medicine as a treatment for muscle soreness (Costello et al., 2016). It involves single or multiple brief exposures (two to four minutes) to extremely cold temperatures (-80 to -190°C) that are either achieved via liquid nitrogen or refrigerated cold air. During exposures, athletes wear minimal clothing, gloves, ear protectors, a nose and mouth mask, as well as dry shoes and socks to reduce the risk of cold-related injury.

Potentially, the significant cold temperatures (in comparison to CWI) may lead athletes to believe that recovery will be enhanced. Similar to CWI, the benefits of WBC are hypothesised to be related to cold-induced vasoconstriction that may limit oedema, inflammation and secondary damage to the muscle, and an analgesic effect of cold that may limit soreness.

In a review conducted by Bleakley et al., (2014) it was concluded that WBC offers improvements in subjective recovery and muscle soreness, but there were few benefits for recovery of muscle function following a variety of exercise stresses. However, these outcomes were based on the limited research that has been conducted to date. Similar to research investigating other recovery interventions, the method of application of WBC, the mode of exercise and the training status of participants vary between studies, which impacts on the conclusions that can be drawn. For example, Costello et al., (2012) demonstrated that WBC had no effect on alleviating muscle soreness or enhancing muscle recovery following WBC applied 24 hours post-exercise. However, Ferriera-Junior et al., (2014) demonstrated that immediate exposure to WBC following drop jumps prevented muscle swelling and resulted in quicker recovery of muscle strength. The

distinguishing factor between these studies is when WBC was applied. Applying 24 hours post exercise may not coincide with the inflammatory response and as a result may be too late to influence recovery processes. Recently, Russell et al., (2017) investigated the effect of WBC following repeat sprint exercise on a range of recovery markers in professional academy footballers. It was found that although WBC increased testosterone concentrations for 24 hours, no other markers of physiological, performance or perceptual recovery were affected.

Many of the positive results in favour of WBC have come from studies investigating its repeated use over days. Both Hausswirth et al., (2011) and Fonda and Sarabon, (2013) investigated the effects of WBC on performance and perceptual markers following muscle damage using three and five sessions of WBC, respectively. Both studies reported that WBC resulted in faster recovery of peak torque and lower perceptions of pain compared to the control group. Methodological differences in relation to mode of exercise, temperature, exposure time and outcome variables make it difficult to establish whether WBC is effective and how best to apply it.

It is purported that WBC may confer an added advantage in comparison to CWI due to the significantly colder temperatures athletes are exposed to. This may produce a large temperature gradient for tissue cooling. However, air has poor thermal conductivity in comparison to water that prevents significant subcutaneous and core body cooling. In relation to body temperature changes, Costello et al., (2012) investigated the effect of four minutes of CWI (8°C) and WBC (-110°C) on muscle, skin and core temperature. Both treatments elicited similar effects on decreases in muscle and core temperature, but WBC lead to greater changes in skin temperature. The authors stated that the colder temperature of WBC compensated for the reduced thermal conductivity of air (Costello et al., 2012). More recent research (Costello et al., 2014) has demonstrated that although WBC leads to greater immediate decreases in skin temperature that this effect is reversed from 10 to 60 minutes post. This suggests that although WBC can stimulate greater reductions in skin temperature, the recovery back to baseline is quicker than CWI (skin remains cooler with CWI). However, CWI is routinely applied for approximately ten minutes, which may lead to similar initial reductions in skin temperature as WBC. Further to these findings, although skin temperature is reduced in both WBC and CWI, neither is sufficient enough to elicit an analgesic effect (Costello et al.,

2014). It remains to be elucidated if different cooling protocols elicit more optimal effects.

Although there may be minimal differences in the cooling effects of WBC and CWI, only one study known to date has compared the efficacy of these interventions on muscle function and soreness. Abaidia et al., (2016) recently demonstrated that participants exposed to CWI had lower levels of muscle soreness and CK, higher perceptions of recovery and a greater attenuation of decrements in muscle power but not muscle strength in the days post eccentric exercise than those completing WBC. It can be speculated that the faster recovery with CWI is partly linked to the thermal conductivity of water, hydrostatic pressure (Abaidia et al., 2016) and potentially longer reductions in skin temperature (Costello et al., 2014). The evidence in support of this expensive recovery intervention is limited. However, future research is required to advance what is known in relation to the physiological rationale for WBC, and in relation to CWI.

Compression garments

Compression garments are increasingly used within sport. It is claimed that their use can improve recovery from strenuous exercise (Hill et al., 2014a). The purported physiological benefits may be linked to the creation of an external pressure gradient and/or enhanced blood flow that both may reduce swelling, and/or enhance the removal of waste products and muscle metabolites (Hill et al., 2014a).

Similar to other recovery interventions, the results are equivocal, which is likely due to the variety in mode of exercise, application of the garment, training status of participants and/or outcome measures utilised. In a recent meta-analysis, Hill et al., (2014a) found that when compression garments are worn after, or during and after strenuous exercise, there is a moderate benefit in reducing muscle soreness and CK concentrations, and improvements in recovery of muscle strength and power. However, in the same year, the same group demonstrated that the use of a lower limb compression garment worn for 72 hours after a marathon had no effect on improving recovery of muscle performance or the removal of serum markers of muscle damage and inflammation (Hill et al., 2014b). There was, however, a significant reduction in perceived levels of muscle soreness at 24 hours in those that wore the compression garment.

There may be many reasons for the conflicting findings, however; much of the discrepancy in results has been linked to the pressure exerted by the garment. A variety of compression garments are utilised in research and the pressure applied, which is not routinely reported, is significantly affected by garment type, size and posture assumed by the athlete (Brophy-Williams et al., 2015). In respect of this, recent research has demonstrated that the pressure exerted likely plays a role in the efficacy of compression garments. Hill et al., (2017) compared the effectiveness of high (14.8 ± 2.2 mmHg at the thigh; 24.3 ± 3.7 mmHg at the calf) and low (8.1 ± 1.3 mmHg at the thigh and 14.8 ± 2.1 mmHg at the calf) compression garments on recovery following drop jumps. The authors concluded that the pressure exerted by a compression garment did affect recovery following EIMD, with a higher pressure more beneficial for recovery of muscle function (Hill et al., 2017), a key consideration for applied practitioners and athletes.

Although there is evidence to suggest garments that exert high pressures are more effective for recovery, there are large variations in the degree of pressures exerted across a population. This is likely due to differences in limb and tissue size (Hill et al., 2017). However, athletes must be aware that higher does not necessarily equal better, and there may be an optimal level of pressure required. Although low levels of compression may be insufficient to impact on physiological processes such as blood flow and osmotic pressure, compression that is too high may restrict blood flow (Hill et al., 2017) and thus negatively impact on recovery. Defining the optimal level of pressure is difficult due to reasons previously discussed (individual variation in limb and tissue size).

Neuromuscular electrical stimulation (NMES)

Neuromuscular electrical stimulation (NMES) involves the application of surface electrodes over muscle motor points to stimulate visible muscle contractions and enhance blood flow (Malone et al., 2014, Taylor et al., 2015). It is purported that an increase in blood flow will aid the repair of skeletal muscle by increasing the delivery of oxygen, hormones and restorative nutrients (Wilcock et al., 2006), and a potential reduction in inflammation (Wilcock et al., 2006, Barnett, 2006).

Malone et al., (2014) conducted a meta-analysis on the efficacy of NMES for recovery compared to active and passive recovery. Through the

evidence they concluded that NMES has positive effects on muscle soreness and perceptions of well-being, however, it was not more effective than both passive and active recovery in improving the recovery of muscle performance and function. Similar to most other recovery interventions, there is considerable heterogeneity within existing research protocols (Malone et al., 2014). One of the key areas that may account for this heterogeneity is the application of NMES with regards to the stimulation intensity and duration the device is worn. A variety of stimulation intensities are used that make optimal parameters difficult to conclude on. Achieving the optimal intensity is important as muscle activation must be induced but should not lead to muscle fatigue (Malone et al., 2014). Furthermore, considerable individual variability can exist due to differences in adipose tissue and an individual's perception of pain and discomfort (Malone et al., 2014).

The studies utilised by Malone et al., (2014) predominantly applied NMES for 20–25 minutes, with one study using it for 60 minutes (Westcott et al., 2011); these studies did not demonstrate positive outcomes for the recovery of muscle function. Regarding the training and competing athlete, measures of muscle function and performance are of key importance. Therefore, more recent research has attempted to address the potential limitations of previous work (application time and stimulation intensity). In this study, NMES was worn for eight hours at a specified stimulation intensity (Frequency of 1 Hz; Current of 27 mA; Pulse width of 140 μs) post high-intensity sprints in professional rugby union and academy soccer players (Taylor et al., 2015). Results demonstrated that in comparison to a control, NMES was beneficial in reducing muscle soreness and CK, whilst improvements in muscle function at 24 hours were reported (Taylor et al., 2015). This research suggests that to achieve enhanced recovery of muscle function, the optimal duration of NMES application is likely to be hours rather than minutes. However, this study only assessed recovery up to 24 hours post. Recovery interventions are utilised in both training and competition scenarios, therefore, it is important to understand their efficacy in the days (e.g., 72 hours) post strenuous exercise. Therefore, future research investigating the efficacy of NMES should focus on tracking recovery over 72 hours (as a minimum) and continuously applying NMES over hours (as opposed to minutes).

CONCLUSION

It is clear that research investigating the efficacy of many recovery interventions is still in its infancy. Research into several strategies has produced conflicting findings which are likely related to differences in application of the strategy, exercise stress, outcome measures and participant training status. Further to this, the majority of research has been conducted in males only, and given the reported sex differences in stress responses, it should not be assumed that the results from such studies are directly transferable to females.

Regarding the use of interventions for acute recovery (e.g., 72 hours post exercise) then as far as the authors are aware there is no current evidence that the use of the strategies discussed in this review are harmful. However, the information discussed has not focussed on long-term or chronic repeated use of these recovery strategies. The next section of this chapter will focus on the application of recovery interventions to practice.

SECTION 2: APPLYING RECOVERY STRATEGIES IN PRACTICE

Recovery versus adaptation

In Section 1, we discussed that following training there is a physiological stress response that reduces performance potential. In order to facilitate quicker return to play or training, athletes utilise recovery interventions (such as those in Section 1) which act upon the physiological stress responses induced through vigorous exercise. The postulated benefits of such interventions are linked to a reduction in muscle soreness and accelerated recovery of muscle function. However, subsequent to the aforementioned stress responses (muscle damage, inflammation, oxidative stress) is a cascade of molecular signals that initiate adaptive processes, providing the desired outcomes of training (i.e., anabolism, angiogenesis etc). It is now well acknowledged that inflammation and protein breakdown of the muscle are vital to repair, regeneration and physiological adaptation. Therefore, there is an increasing volume of research investigating the adaptive response to training when recovery interventions are applied. Although this paradigm is in its infancy, the majority of the research has focussed on the use of CWI, therefore, this section will focus on CWI research only with regards to its potential impact on physiological adaptation. The research in this area can be categorised into two themes, the use of CWI following 1) strength training and 2) endurance training.

1) The use of CWI during strength training

Research has demonstrated that using CWI during a block of strength training blunts aspects of physiological adaptation (Frohlich et al., 2014, Roberts et al., 2015, Yamane et al., 2015). Roberts et al., (2015) investigated the chronic use of CWI following lower-body strength training session (twice per week) for 12 weeks. It was found that although there were significant increases in muscle mass, maximum strength and rate of force development, this change was significantly less in the CWI condition compared to an active control. Furthermore, type II muscle fibres, total cross-sectional area and maximum isometric torque significantly increased

in active recovery, but this was not observed in those receiving CWI. The authors concluded that CWI substantially attenuated long-term gains in muscle mass and strength. In an attempt to understand the underpinning physiology, Roberts et al., (2015) measured p70S6K phosphorylation, total protein content and satellite cell numbers from muscle biopsies following a single leg strength exercise. p70S6K is a key regulator in the mammalian target of rapamycin (mTOR) pathway of protein synthesis, and thus any down regulation in p70S6K is likely to be reflective of attenuated protein synthesis, potentially impacting long-term adaptation. The results demonstrated that CWI suppressed the activity of satellite cells and p70S6K during recovery from strength exercise. Therefore, this research demonstrates that CWI may downregulate muscle protein regeneration, impacting on physiological and performance adaptation. However, this research did not include a control group, and further research is required to confirm these findings. It is assumed that the downregulation of this pathway is linked to a reduced inflammatory response. However, using the same data, Peake et al., (2017b) demonstrated that CWI did not restrict inflammation in comparison to an active control. Therefore, the restriction of kinases involved in the mTOR pathway is not due to cold-induced vasoconstriction that reduces the inflammatory response, and thus remains unknown.

2) The use of CWI during endurance training

A number of studies have demonstrated that CWI enhances adaptation from endurance exercise (Halson et al., 2014, Ihsan et al., 2014, Ihsan et al., 2015, Joo et al., 2016). Halson et al., (2014) found that during 39 days of structured training in nationally competitive level endurance cyclists, using CWI four times per week resulted in a greater increase in repeat cycling performance. In an attempt to understand the physiological mechanisms, Ihsan et al., (2015) investigated changes in total and phosphorylated 5’ AMP-activated protein kinase (AMPK) and peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC-1α) over four weeks of endurance training with or without CWI. PGC-1α is well accepted as a critical regulator of mitochondrial biogenesis in skeletal muscle whilst AMPK is an upstream regulator of PGC-1α (Jager et al., 2007). The authors reported that there was a significant increase in both total and

phosphorylated AMPK in CWI versus the control group, and although no significant difference was observed for PGC-1α, there was a large effect size in favour of CWI. Therefore, it was concluded that regular CWI enhances p38 AMPK and possibly mitochondrial biogenesis (Ihsan et al., 2015). In support of this research both Ihsan et al., (2014) and Joo et al., (2016) have found that both PGC-1α and vascular endothelial growth factor (VEGF) messenger ribonucleic acid (mRNA) expressions are increased when CWI is used following a bout of endurance exercise, concluding that acute post-exercise cooling may provide a suitable strategy for enhancing mitochondrial biogenesis (Ihsan et al., 2014). Joo et al., (2016) found that CWI without prior exercise also mediated the increased activation of these pathways, but that the combination of exercise and CWI led to a greater expression. Therefore, CWI potentially may be used to modulate mitochondrial biogenesis following endurance exercise.

CONCLUSION

Following strength training, CWI is implicated in the blunting of adaptive responses, and therefore this should be considered when physiological and performance adaptation is the priority rather than recovery. Conversely, the evidence suggests that during endurance training periods, athletes and applied practitioners may want to implement CWI given the reported benefits on mitochondrial biogenesis. In summary, the research reviewed in this section demonstrates the importance of considering the specific scenario when considering applying recovery strategies.

Guidelines for practical application

A number of key questions should be taken into account when considering implementing recovery strategies and making decisions on the most appropriate strategy to utilise:

- Scenario – Training or competition?
    - Competition: The primary aim of competition is to ensure that the athlete can perform optimally in their sport. During these scenarios, select a recovery strategy that has been demonstrated

to limit decrements and/or enhance recovery of performance and limit perceptions of muscle soreness.

  - Training: If the aim of this training period is physiological adaptation, then limit the chronic use of recovery strategies when there is evidence or potential for those interventions to inhibit adaptive responses involving inflammation and oxidative stress. In training scenarios, the focus should be placed on the foundations of good sleep and nutrition practices.

- Type and timing of stress – What is the athlete recovering from and when is it happening?
  - Each category of exercise stress (mechanical, metabolic, mixed) elicits different physiological responses (magnitude and timing) dependent upon the type of exercise performed. Therefore, it is important to understand the timing of the specific stress response occurring, ensure the recovery intervention selected has been shown to reduce that response and ensure that the intervention is applied at the correct time in relation to the stress response (Figure 11.1).
  - Example 1 – Following a heavy resistance training session the aim may be to limit the breakdown of muscle protein structures and/or increase muscle protein synthesis. Therefore, a CHO-protein supplement would be most suited to this scenario.
  - Example 2 – Following high-intensity endurance cycling, there is likely to be an elevated inflammatory response which may inhibit subsequent day's performance (important in stage races where multiple, consecutive days' performance are required). The aim of CWI is to reduce blood flow that may limit the inflammatory response and given the inflammatory cascade is most active in the hours following exercise cessation, CWI should be applied immediately following performance. Alternatively, however, the aim of NMES is to increase blood flow (which may exacerbate inflammation) in order to enhance the delivery of oxygen and nutrients. Therefore, the optimum time for application is once the inflammatory process has occurred (i.e., > 6 hours post-exercise)
- What about nutrition and sleep, the foundations of recovery?

- o Do not forget, good nutrition and sleep form the foundations of recovery and should be prioritised.
- o It is important that athlete sleep is of optimal quality and quantity (see Samuels, 2009 for review); appropriate nutritional strategies that support rehydration, muscle glycogen resynthesis and protein metabolism are utilised (Figure 11.1), and mental fatigue/stress is limited via adequate rest.

- Are recovery interventions for everyone at every time?
  - o Recovery interventions should not be treated using a one-size-fits-all approach. As previously discussed the scenario (training vs. competition) and exercise stress should be accounted for. However, even within one team there is a range of positional demands and training statuses. These factors may impact on the magnitude and timing of the physiological stress response and thus one recovery intervention may not be required for all athletes within that team.

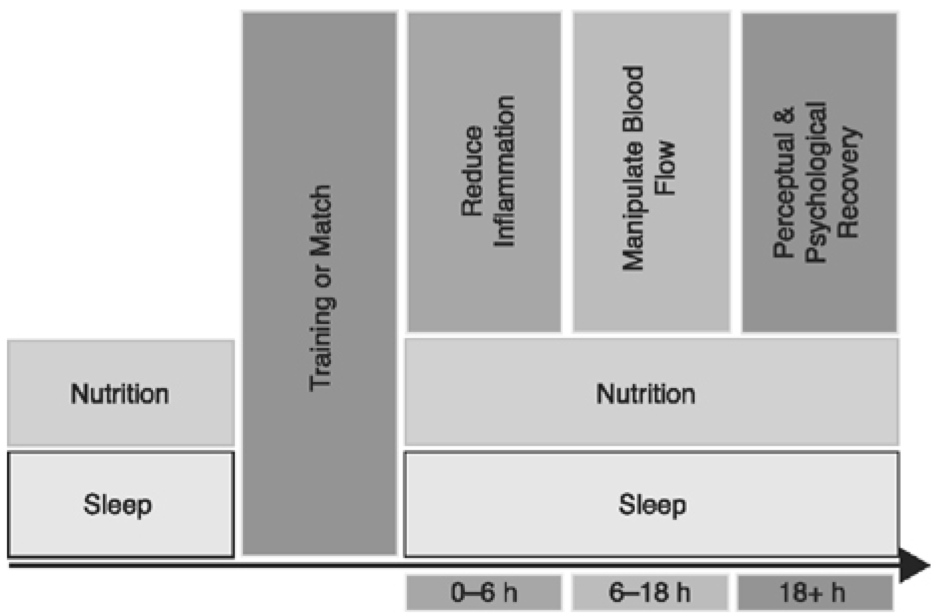

FIGURE 11.1 Timing of recovery strategy aims, underpinned by foundations of optimal sleep and nutrition.

Practical recommendations for acute recovery

Once the most appropriate recovery intervention has been selected for the scenario, type and timing of stress and the individual, and the foundations

of recovery are built into the programme, Table 11.1 provides practical recommendations for their use (in acute situations).

TABLE 11.1 Practical recommendations for the use of various recovery interventions

Recovery intervention	*Practial recommendations*
CHO/Protein	• Consume immediately following heavy resistance-based exercise • Milk (cow's) has demonstrated positive effects in terms of muscle function
Antioxidants and functional foods	• Use functional foods rather than antioxidant supplements to accelerate recovery from metabolically stressful exercise (e.g., endurance cycling) • Avoid antioxidant supplements during training phases
Cold water immersion	• Apply CWI immediately following high-intensity exercise • Use a temperature in the range of 11–15˚C for 11–15 minutes • Most promise in alleviating perceptions of muscle soreness
Whole body cryotherapy	• Little support for this expensive intervention and lacking in high-quality research • Potential for positive recovery effects if applied immediately following high-intensity exercise or over a number of days
Compression garments	• Apply following muscle damaging or high-intensity performances • Maintain compression garment's application for up to 72 hours post-exercise, or until next performance • Garment must apply sufficient pressure to impact on blood flow, but not restrict it
NMES	• Duration of eight hours has demonstrated the most promise in terms of effects on performance and muscle soreness • Stimulation intensity must be enough to elicit muscle actions but not fatigue (or discomfort)

CONCLUSION

There is a clear desire for athletes to be able to accelerate recovery from exercise. This chapter has highlighted the evidence underpinning the use of a range of recovery strategies commonly used within applied practice. Within many of the modalities reviewed there are conflicting reports on the efficacy of such practices. Therefore, it is difficult to make concrete statements with regards to application. Despite this, there is little evidence to suggest that recovery strategies (those discussed in this chapter) are harmful to the athlete, and as a result when accelerating recovery is the only consideration, the application of recovery interventions (at the right time) seems appropriate. Conversely, in periods of training where physiological adaptation is the desired outcome, and given the emerging evidence suggesting blunting effects, serious consideration should be given with regards to the use of certain recovery interventions. In summary, practitioners should consider the scenario and what the goal is before making a decision on whether to apply recovery strategies.

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CHAPTER 12

Fitness testing and data analysis

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INTRODUCTION

This chapter provides an overview of the main factors that should be considered when designing and conducting fitness testing batteries and when subsequently analysing the resultant data. The chapter is presented in the general order in which the process of designing and implementing a fitness testing battery is completed. This approach reflects a clear step-by-step process that practitioners should adhere to, where possible, in order to design and implement effective fitness testing batteries and ensure that resultant data is analysed correctly. Specific examples of how the main factors for consideration apply to commonly utilised fitness tests are provided throughout. The information presented in this chapter should, therefore, help practitioners with the design of their own fitness testing batteries and data analysis techniques.

WHY FITNESS TEST?

Conducting fitness testing batteries with an individual athlete or a squad of athletes provides practitioners with an objective method of monitoring changes in specific fitness qualities (e.g., strength, power, speed, etc.) over time. The specific fitness qualities that are assessed as part of fitness testing batteries should be determined following a needs analysis of the athlete’s sport, with, where appropriate, consideration also given to different

positional demands of the sport. The results gleaned from fitness testing batteries should be used to inform the athlete’s upcoming training priorities and, if applicable, provide insight into the success of the athlete’s previous training cycle(s). Fitness testing results should, therefore, be used by practitioners to facilitate the construction of effective training programmes by identifying a given athlete’s area(s) for improvement and highlighting what may or may not have worked well for said athlete in the previous training cycle(s).

WHEN TO TEST

Fitness testing should, ideally, initially take place at the beginning of the pre-season training cycle as the results of testing conducted at this time point would provide a baseline of fitness data which will inform this initial training block (based on identified strengths and weaknesses), and serve as a reference point for data collected as part of further fitness testing sessions conducted throughout the remainder of the season. Ideally, the same fitness testing battery would initially be conducted twice (typically interspersed by a two to seven day gap) at the beginning of pre-season in order for the measurement error of each test (and the athlete or squad tested where appropriate) to be established; thus, the computation of both between trail and between day variability is known. This will inform the practitioner of what a meaningful change in each tested fitness parameter would be for a given athlete or squad of athletes, and thus will help the practitioner to identify ‘true’ changes in a particular test score in subsequent fitness testing sessions. If it is not appropriate or feasible to test the athlete(s) twice in fairly quick succession, and thus for athlete/squad specific-test measurement error to be established, then practitioners should use published (preferably subject-specific) test measurement error values to help identify meaningful changes in performance.

After testing at least once at the beginning of the pre-season training cycle, the scheduling of subsequent fitness testing sessions will vary from sport to sport, depending upon several factors such as the duration and scheduling of the season. Generally, practitioners should at least aim to fitness test athletes again at the end of the pre-season training cycle so that athletes’ level of preparedness for competition can be benchmarked against both published/squad normative data and the fitness test results gathered at

the onset of the pre-season training block (i.e., to inform the magnitude of improvement/decline in each assessed fitness quality). Preferably, fitness testing will take place at some point within the competitive season (particularly for sports whose season includes a break from competition) to assess the physical demands of competition on the athletes' fitness characteristics. If this is not possible then an alternative solution could be to select one or two key fitness tests (e.g., the vertical jump) to conduct on a frequent basis as part of continual athlete monitoring procedures.

Although fitness testing scheduling throughout the season may vary between sports, it should be conducted when athletes are rested (i.e., sufficient time [~48 hours] must have lapsed post the last match/intense training session). Additionally, when periodic fitness testing does take place, athletes should be tested at approximately the same time of day to account for circadian rhythms and body temperature, which impacts several physical and morphological qualities such as muscle strength (Gauthier et al., 2001; Teo et al., 2011), power output (Teo et al., 2011; West et al., 2014) and tendon stiffness (Onambele-Pearson & Pearson, 2007; Pearson & Onambele, 2006).

TEST SELECTION

Once a rationale for conducting fitness testing has been determined and the appropriate timing of fitness testing has been identified, it is important to decide upon which test(s) to conduct. This will depend upon the previously identified demands of the sport (as achieved through conducting an evidence-based needs analysis) and, if applicable, will consider position-specific physical requirements. Additionally, other factors such as the athlete's age and training status should also be considered when determining appropriate test selection. For example, a commonly used and widely accepted measure of ascertaining an athlete's maximal dynamic strength capacity is the one repetition maximum (1-RM) test. This type of test requires athletes to perform up to five single repetition sets (after an appropriate warm-up) of given exercise with a gradually increasing load until an incomplete attempt occurs (Baechle et al., 2008). The penultimate repetition (i.e., the last successful lift achieved) is then considered to be the athlete's 1-RM load for that exercise. It may, however, be deemed inappropriate to conduct a 1-RM test with weaker or beginner athlete(s). In

this case, a 3- or 5-RM test of dynamic strength might be more appropriate, assuming the athlete(s) can perform the selected exercise with correct technique, as it has been shown that the load lifted in these multiple repetition tests of dynamic strength can be used to predict the 1-RM load (Reynolds et al., 2006). It should be noted, however, that the ability to accurately predict 1-RM loads from multiple repetition tests of strength depends upon the exercise used (Hoeger et al., 1990; Shimano et al., 2006), and this should be considered in advance of testing. It is worth noting, however, that the 1-RM power clean test, which requires a higher degree of technical competency than commonly tested compound exercises such as the back squat, has been shown to be reliable even in youth (Faigenbaum et al., 2012) and inexperienced collegiate (Comfort & McMahon, 2015) athletes, following a sufficient period of familiarisation.

When an athlete does not demonstrate correct exercise technique at high loads but determining maximal strength for the athlete is deemed to be a requirement, then performing a multi-joint isometric 'strength' assessment, such as the isometric squat or mid-thigh pull, could be a suitable option. Isometric strength tests require minimal familiarity (providing that the athlete puts in a maximal effort during each repetition), skill and time when compared to dynamic strength tests which arguably makes them better suited to testing both beginner/weaker individuals and groups of athletes. These factors also enable multi-joint isometric tests to yield high reliability and low variability values (Blazevich et al., 2002; Comfort et al., 2015; Dos'Santos et al., 2016; Haff et al., 2015; Thomas et al., 2015), thus increasing the sensitivity of these tests for detecting 'true' performance changes. Additionally, strong associations have been reported between isometric and dynamic strength tests (Beckham et al., 2013; McGuigan et al., 2010; Nuzzo et al., 2008), which means that the values derived from isometric strength tests can be used to inform dynamic load prescription for a given training cycle by applying the relevant prediction equation (De Witt et al., Publish Ahead of Print). A limitation of isometric strength tests, however, is that they require a force platform, which, although cheaper validated force platforms are now available, could restrict accessibility for many athletes, and the capacity of fixing a barbell at the required position (i.e., a custom rig or power rack).

In addition to isometric tests offering a suitable alternative to dynamic 1-RM testing, recent studies have shown that 1-RM values attained in a range

of bench press (Bosquet et al., 2010; García-Ramos et al., 2016a; Jidovtseff et al., 2011) and squatting derivatives (Bazuelo-Ruiz et al., 2015; Conceição et al., 2016) can, in most cases, be almost perfectly predicted from the barbell velocity measured using a linear position transducer during these exercises performed with sub-maximal loads (and applying the relevant prediction equations). This approach, like some of the other approaches discussed earlier, may help to overcome the potential for safety/injury risk issues that are associated with 1-RM testing of beginner/weaker athletes. Similar to isometric strength tests and equipment, linear position transducers have been shown to yield valid and highly reliable measurements of system and barbell velocity, which enables this method to be compared to gold standard methods of assessing velocity (e.g., force platforms if measuring system velocity) and used to detect performance changes (García-Ramos et al., 2016b; Garnacho-Castaño et al., 2015; Giroux et al., 2015).

Maximal sprint performance is highly regarded as an important determinant of performance in many sports, but the distance(s) over which maximal sprint performance should be assessed will depend on the typical sprint distances covered during competitive sport play and, preferably, position-specific sprint distances should be considered. Similarly, if jump testing is deemed to be important to include within a testing battery for a given sport, then attention should be given to the type(s) of jumps performed in competition. For example, are the jumps performed in the sport usually performed unilaterally or bilaterally, with or without a countermovement, vertically or horizontally? Each of these factors should be considered when deciding upon the type(s) of jump test(s) to conduct. There are also other reasons why specific jump tests may be selected as part of the fitness testing battery, even if they are not commonly performed as part of the athlete’s sport. For example, the squat jump (SJ) might be tested along with the countermovement jump (CMJ), even if the former is not typically performed as part of the sport, simply in order to provide an indication of how well an athlete can utilise the stretch-shortening cycle (SSC). As such, an eccentric utilisation ratio (EUR) can be calculated (EUR = CMJ height ÷ SJ height) with a ratio of >1.0 demonstrating that the use of the SSC results in a greater jump height, however, if the ratio is <1.0 the SSC needs to be developed (McGuigan et al., 2006). Therefore, fitness test

selection will be informed by both the typical demands of the sport and the general athletic qualities that underpin these demands.

EQUIPMENT SELECTION

Once it has been decided which test(s) will be conducted, the next step is to decide which equipment to use for the selected test(s). Ideally, the gold standard equipment for testing a particular fitness quality should be used where possible; however, this may be unrealistic from both an accessibility and time perspective for many practitioners. An example of the latter is that although some practitioners working with a team sport may have access to expensive direct gas analysers for measuring maximal aerobic capacity, it would take a very long time to assess a full squad on this parameter. Instead, practitioners should consider using alternative equipment that has been validated against the currently considered gold standard equipment when access to the latter is either impossible or unrealistic. In referring back to the aforementioned example of measuring maximal aerobic capacity, basic equipment such as cones, a measuring tape and an audio device could be used to conduct the Yo-Yo Intermittent Recovery Test (YIRT) or Multi-Stage Fitness Test (MSFT), which have both been shown to provide a valid, field-based alternative to direct gas analysis (Krustrup et al., 2003; Ramsbottom et al., 1988).

In terms of quantifying jump performance, a force platform is considered to be the gold standard equipment (García-López et al., 2013), particularly when using the take-off velocity method (Moir, 2008), but similar to direct gas analysers, force platforms may be inaccessible for some practitioners due their general cost. In recent years, however, many cheaper alternatives (that calculate jump height using the flight time method) have been validated. For example, photoelectric cells have been shown to yield similar jump height values to those attained using a force platform (García-López et al., 2013; Glatthorn et al., 2011). Jump mats have generally been shown to yield inaccurate but reliable measurements of jump height (García-López et al., 2013; McMahon et al., 2016b; Nuzzo et al., 2011), meaning that their values can be easily and correctly converted through published equations (García-López et al., 2013; McMahon et al., 2016b). It is worth taking into consideration that the accuracy of jump height values attained from jump mats depends on the type of jump being performed and the level of

performer, with lower accuracy seen for short contact jumps, such as the drop jump (Kenny et al., 2012), and for athletes who can jump very high (Whitmer et al., 2015). An even cheaper alternative method of measuring jump height from flight time is through iPhone apps, with jump height attained using the My Jump app, for example, showing almost perfect agreement with values attained from a force platform (Balsalobre-Fernández et al., 2015). It must be noted here that the flight time method of calculating jump height is prone to errors when compared to the take-off velocity method (Moir, 2008) due to, for example, tucking of the legs during the flight phase, and so standardising the instructions given to athletes regarding the flight phase of the jump is especially important when assessing jump height in this manner (see the 'Standardising Protocols' section for more information).

Fully automatic timing systems, such as those used at international athletics events, are considered to be the gold standard equipment for measuring linear sprint speed (Haugen & Buchheit, 2016; Haugen et al., 2012b). These systems are, however, very expensive and impractical for most practitioners to utilise (Haugen & Buchheit, 2016). Due to this, several alternatives of varying practicality have been suggested in the literature such as electronic timing gates, laser guns and high-speed videography (Haugen & Buchheit, 2016). Of these suggestions, electronic timing gates are perhaps the most practical in terms of accessibility and speed of data processing, and thus are frequently used in both research and applied settings (Haugen & Buchheit, 2016). The accuracy of sprint times recorded by electronic timing gates do, however, depend on several factors, including the type of photocells used (e.g., single- versus dual-beam). Unlike single-beam electronic timing gates (Earp & Newton, 2012; Haugen et al., 2014), dual-beam electronic timing gates have been shown to reduce the likelihood of an athlete's arms or legs breaking the beams, rather than their hips as is preferred (Yeadon et al., 1999). Nevertheless, single-beam electronic timing gates are still commonly used in both research and applied settings (Carr et al., 2015; Dos'Santos et al., Publish Ahead of Print), possibly due to them being cheaper to purchase (Earp & Newton, 2012), and they have been validated against fully automatic timing systems (Haugen et al., 2012b). Split-beamed and post-processing timing gates are also available for use, although the errors in sprint times attained by split-beamed timing gates are similar to those measured via single-beamed

systems (Haugen et al., 2012a, 2013), and the test-retest reliability of post-processing timing gates is currently unknown (Haugen & Buchheit, 2016).

Although gold standard equipment can provide more detail about a particular fitness characteristic, in reality, the type of equipment selected by practitioners to test specific fitness qualities depends upon accessibility, feasibility and affordability. Whether using gold standard equipment or validated alternatives, it is vitally important to understand the associated measurement error to allow accurate decisions to be made regarding training adaptations (this will be discussed in detail in the 'Interpreting results' section). As some validated equipment alternatives of a similar cost have larger measurement error than others, it would be prudent to choose the alternative equipment that has the highest degree of accuracy. Another important consideration when selecting equipment for testing certain fitness characteristics is sampling frequency capability. For example, if assessing vertical jump height using a force platform, it has been suggested that a minimum sampling frequency of 1000 Hz should be used (Owen et al., 2014; Street et al., 2001). On the other hand, a sampling frequency range of 500–2000 Hz had no effect on force-time variables assessed during the isometric mid-thigh pull (Dos'Santos et al., 2016). Alternatively, it has been recently suggested that the minimum sample frequency of linear position transducers for yielding quality movement velocity data is 25 Hz, and that sampling above this frequency does not improve recording precision and may, if an excessively high sample frequency is selected, have adverse effects on data quality (Bardella et al., Publish Ahead of Print). Each of these factors should be considered in order to inform the best equipment choice for a given purpose and budget.

STANDARDISING PROTOCOLS

Another very important factor to consider as part of the fitness testing process is the standardisation of protocols for the test(s) to be conducted, as this will affect the reliability, variability and comparability of the data collected. For dynamic strength tests, the standardisation required might be as simple as ensuring correct barbell placement (e.g., high or low barbell position in the back squat (Wretenberg et al., 1996)), the range of motion (e.g., squat depth) is consistent (Bryanton et al., 2012) and athletes put in a maximal effort. The latter point is, indeed, a requirement of all maximal

tests. Additionally, the rest period prescribed between trials may also affect the results gathered. For example, during 1-RM back squat testing, there were no significant differences in the ability to lift a maximal load when subjects were given one, three or five minutes' rests between lifts (Matuszak et al., 2003), although a greater percentage of the subjects lifted successfully after the three- versus the one-minute rest period (76% versus 94%), suggesting that a minimum of three minutes' rest should be prescribed between 1-RM attempts. Therefore, adequate test-specific rest periods should be prescribed between recorded trials in order to improve test accuracy.

For jump tests, there are many factors that need to be standardised in order to glean consistent data. For example, when jump testing it is important to consider whether or not athletes are permitted to swing their arms, as this has been shown to augment jump height (Hara et al., 2006; Hara et al., 2008; Walsh et al., 2007) but slightly reduce measurement reliability (Markovic et al., 2004). Also, the range of motion (e.g., countermovement or starting depth) (Gheller et al., 2015; Kirby et al., 2011; McBride et al., 2010) and movement/contact time (Arampatzis et al., 2001; Walsh et al., 2004) will influence the resultant jump height and associated force-time variables. This highlights the importance of being clear and consistent with the coaching cues used (e.g., "jump as fast and as high as possible") when jump testing athletes (Louder et al., 2015; McMahon et al., 2016a).

Sprint testing typically has even more methodological factors than strength and jump testing that need to be standardised. For example, the accuracy of sprint times recorded by electronic timing gates will depend upon the height at which they are set up (Cronin & Templeton, 2008; Yeadon et al., 1999), the starting distance from the first beam (Altmann et al., 2015; Haugen et al., 2015) and the starting stance (Frost & Cronin, 2011; Frost et al., 2008; Johnson et al., 2010). Thus, the standardisation of protocols can relate both to the equipment setup and the instructions given to the athlete.

TESTING ORDER

The order of testing is largely dictated by the amount of recovery required following a given test, and so usually baseline measurements of height,

mass, body composition and range of motion would be performed first, followed by skill- and/or speed-based tests (jumps, change of direction/agility and sprints), then maximal strength tests (dynamic or isometric) and finally muscular endurance and/or aerobic capacity tests. In reality, the order of fitness testing will depend upon time/equipment availability and the number athletes being tested, and so a ‘round-robin’ approach might be adopted by practitioners when larger groups of athletes are being tested in a single session. If this is the case, then the testing order for a given athlete should remain the same in subsequent testing sessions and, ideally, the aerobic capacity tests should be performed last by all athletes. The latter is much more feasible when the YIRT or MSFT is conducted in a large space, allowing several athletes to be tested at the same time.

DATA ANALYSIS

After all testing has been completed, at least some (if not most) of the data will need to be processed, as most equipment/software does not provide instantaneous results. Like the testing protocols, the way in which data is analysed post-testing will also greatly influence the accuracy, reliability and variability of the results. The analysis of force-time data is probably the main type of commonly collected data that varies most between published studies and, most likely, in practice. Thus, the standardisation of force-time data analysis is of paramount importance to allow for accurate interpretation of these data. For example, when analysing vertical jump force-time data, the method of determining bodyweight and the thresholds used to identify the onset of movement and the instants of take-off and touchdown will greatly influence factors such as jump height and reactive strength index modified, in addition to variables calculated through forward dynamics procedures such as velocity and power (Eagles et al., 2015; Owen et al., 2014; Street et al., 2001). Additionally, correctly identifying the beginning and end of the braking (if a countermovement is included) and propulsive phases of the vertical jump (Figure 12.1) is important for ensuring correct calculations of several variables in each of these phases, including mean and peak force, time to peak force, rate of force development and impulse. Analysing rate of force development attained in the isometric mid-thigh pull at predetermined time bands, rather than as an

average between the onset of force production and peak force, has been shown to be superior from a reliability perspective (Haff et al., 2015), which further justifies standardisation of the analysis of force-time data for specific tests.

Another consideration when analysing force-time data is how much detail is wanted from the data. For example, only gross measures of a given performance (e.g., mean and peak values of force and related data) are typically reported and compared between fitness testing sessions, whereas comparing performance data sampled throughout the entire movement (which is typically referred to as a temporal phase analysis) can yield far more detailed information about how performances/changes in performances are achieved. Indeed, the latter approach has been recently shown to provide detailed information about neuromuscular fatigue in the countermovement jump (Gathercole et al., 2015), the effect of external load on jump squat performance (Cormie et al., 2008), the effect of weightlifting derivatives on expressions of force (Suchomel & Sole, Publish Ahead of Print) and differences in neuromuscular function between senior and academy rugby league players (McMahon et al., Publish Ahead of Print). Although the temporal phase analysis approach may sound complex, it can actually be conducted in a relatively straightforward manner through the use of customised Microsoft Excel spreadsheets (Figure 12.2). Even if a full temporal phase analysis is considered to be too complex, there is an often underutilised abundance of additional variables that can be calculated from force-time data with just a basic understanding of forward dynamics procedures that can further inform practitioners of their athletes' capacity.

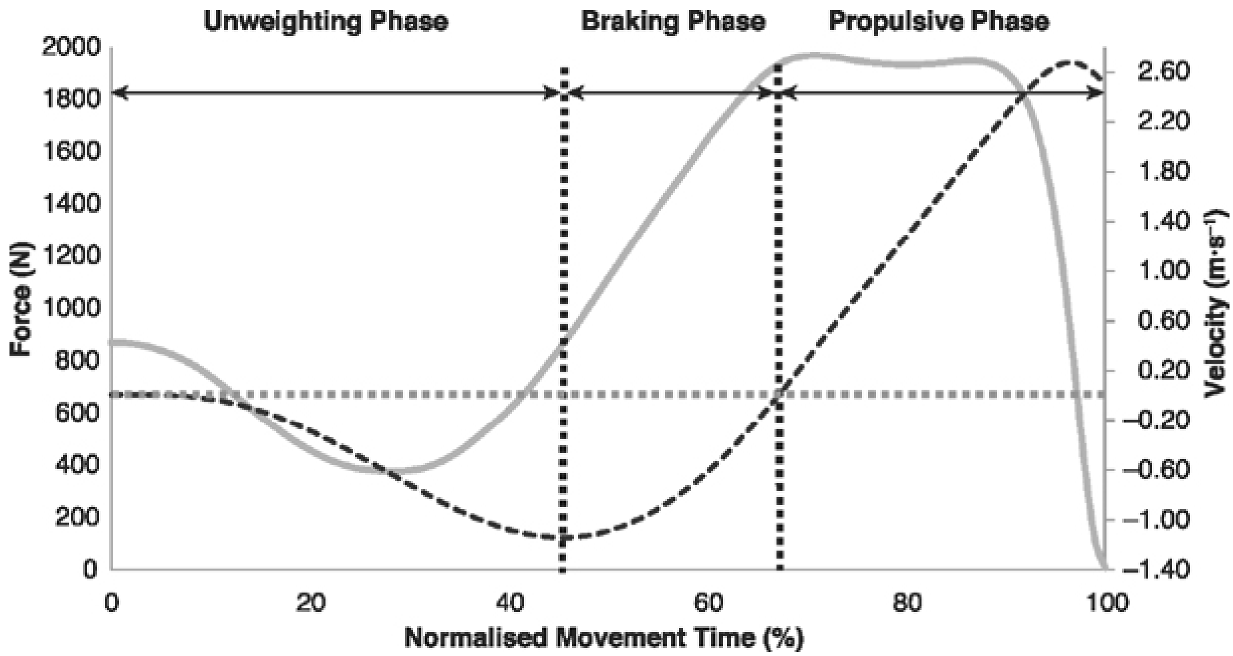

FIGURE 12.1 Example of correctly identifying the unweighting, braking and propulsive phases of a countermovement jump force-time curve (solid grey line) by overlaying the velocity-time curve (dotted black line). The dotted grey line represents zero centre of mass velocity.

To conclude, the standardisation of data analysis is very important and must be applied consistently within and between testing sessions. Where possible, the criterion method (e.g., Owen et al., 2014) for analysing a particular dataset should applied. If a criterion method has not yet been established for analysing a given dataset, or if certain equipment is used that provides instantaneous results via undisclosed data analysis methods, then practitioners should at least be consistent and transparent with their data analysis procedures. When comparing data collected through fitness testing batteries to the normative data from published studies, practitioners should pay particular attention to the methods of data analysis employed in those studies before forming their conclusions. Another point to consider before comparing results between sessions and athletes or to published studies is the normalisation of strength and kinetic data for body mass (or alternatively, employ another appropriate scaling technique, such as those that consider body height and fat free mass), as these data are largely influenced by an athlete's size (Folland et al., 2008).

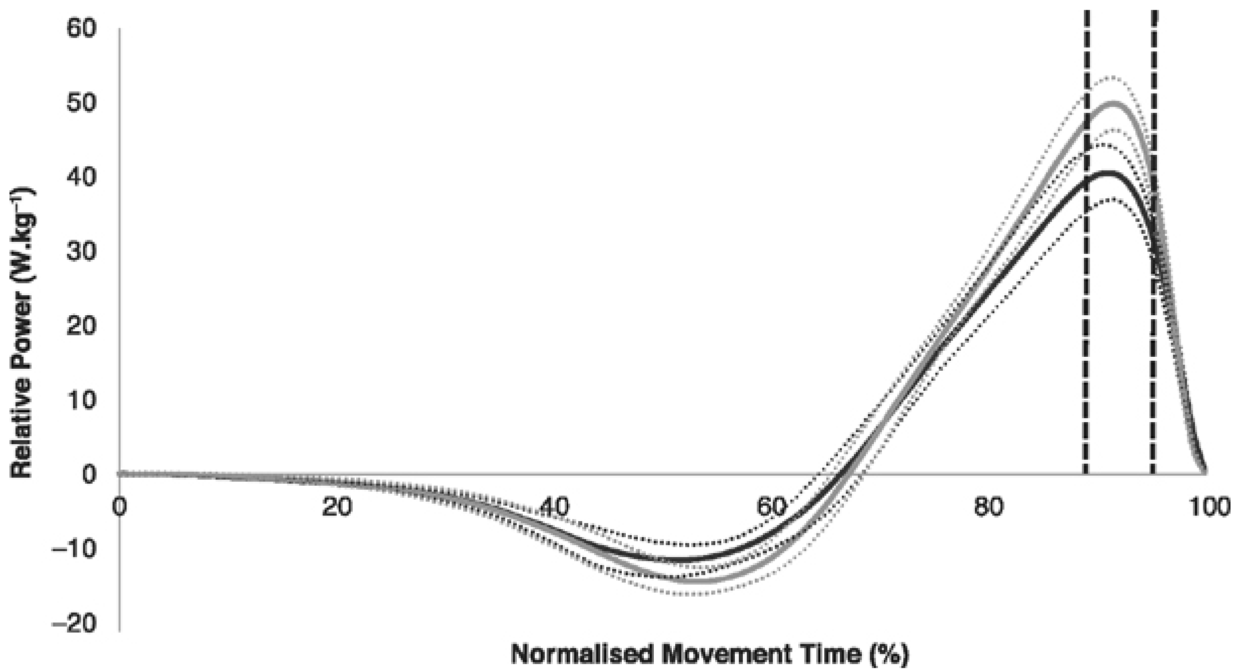

FIGURE 12.2 Example of conducting a temporal phase analysis of relative power-time curves produced by more (grey lines) and less (black lines) powerful athletes. The solid lines represent mean data and the dotted lines represent upper and lower 95% confidence intervals. Non-overlapping areas between curves (e.g., between the dashed vertical lines) denote differences.

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PART 3

Coaching your athlete

CHAPTER 13

Movement screening: An integrated approach to assessing movement quality

Chris Bishop

INTRODUCTION

Movement screening is a concept that has been widely adopted by the strength and conditioning (S&C) community in the past ten to fifteen years. Typical procedures aim to distinguish a level of competency with an associated movement pattern, with such examples including overhead squats, lunges, or landing mechanics. Determining an athlete's competency in a given movement pattern can aid practitioners in decision-making regarding programme design. For example, an excessive forward lean during an overhead squat test may suggest that the athlete in question needs to enhance his or her squat mechanics (commonly, increased dorsiflexion) prior to heavy loading. Similarly, if a jump test is used to assess landing mechanics and excessive knee valgus is present, it may be unwise to programme high-intensity plyometrics. Consequently, movement screens offer S&C coaches the chance to 'get a glimpse' of an athlete's movement profile so that more appropriate decisions can be made on an individual level regarding appropriate exercise prescription. Furthermore, each warm up and training session should also be seen as an opportunity to subjectively identify any dysfunctional movement patterns.

Multiple methods for screening an athlete's movement exist under both low- and high-velocity conditions. For example, the overhead squat and single leg squat provide practitioners with an overall indication of movement quality (Clark and Lucett 2010; Clark et al. 2012). The main focus being to identify movement dysfunction within the screening pattern specific to key joints in the kinetic chain: namely, the ankle, knee, lumbo-pelvic-hip complex, thoracic spine, and shoulder joints. More recently, the Functional Movement Screen (FMS) has come to the forefront of numerous academic publications (Cook et al. 2010; Frost et al. 2012; Fox et al. 2013; Frost et al. 2014; Kazman et al. 2014), which consists of seven tests (one of which is the overhead squat) that aim to challenge movement quality, mobility, and stability. The quality of each test is graded on a numerical scale from zero to three; three being given if the test is performed perfectly, two if the test is completed but with compensations, one if the test is completed but with poor form, and zero if the test is unable to be completed due to the client experiencing pain during its commencement (Beardsley and Contreras 2014).

It has been suggested that these two methods lack the notion of 'sport-specificity' because of the tests occurring at low velocities (Bishop et al. 2015). However, additional screening methods that account for this concept of high velocity also exist: including the Landing Error Scoring System (LESS) (Padua et al. 2009; Padua et al. 2011; Padua et al. 2012), tuck jump assessment (Myer et al. 2008; Klugman et al. 2011; Myer et al. 2011; Herrington et al. 2013; Read et al. 2015), and single leg hop (Barber et al. 1990; Noyes et al. 1991; Ross et al. 2002; Reid et al. 2007; Munro and Herrington 2011; Rohman et al. 2015). The LESS test aims to assess landing mechanics from a procedure similar to that of a typical drop jump methodology, but instead of 'stepping off' a box, subjects are required to jump forward 50% of their own height before rebounding up into a vertical jump. The tuck jump assessment aims to assess landing mechanics from repeated tuck jumps over a continuous ten second period, and the single leg hop has been used as a method of determining levels of asymmetry post-ACL surgery. These high-velocity assessments aim to expose an athlete's imbalances or weaknesses during bilateral and unilateral landing mechanics. Whilst this information can be considered useful, methods are frequently assessed subjectively which could be further enhanced if

objective measures were incorporated into the assessment process (discussed later).

With each test aiming to identify movement quality in their own specific way, it can often be challenging to practitioners to identify which ones are most suitable, practical, and time efficient for assessing movement quality. Therefore, the purpose of this chapter is to critically evaluate current methods for screening movement (which will be identified from existing research) and to suggest a viable system which practitioners may consider moving forward.

OVERHEAD SQUAT

In contrast to the FMS, there is no numerical grading system for the overhead squat specifically. As a result, any research pertaining to this exercise as a movement screen has had to take a ‘laboratory-based’ emphasis. Such studies have included the use of force plates, motion analysis, or electromyography (EMG) in an attempt to quantify specific kinetic and kinematic information.

Atkins et al. (2013) performed the overhead squat on twin force plates on 105 elite youth footballers (U13 to U17 age groups), quantifying vertical ground reaction force (GRF) asymmetries. Significant inter-limb differences ($p < 0.01$) in peak GRF was noted across all age groups (U13 = 6%, U14 = 13%, U15 = 11%, U16 = 9%, and U17 = 4%). It is interesting to note the higher values of asymmetry at the U14 and U15 age groups. Although not accounted for, it was suggested that this ‘spike’ in imbalance may have been a result of maturation, a concept which would seem plausible if the guidelines of the youth physical development model are adhered to (Lloyd et al. 2015). In respect to asymmetry, 15% has been proposed as a threshold for heightened injury risk (Barber et al. 1990; Noyes et al. 1991; Grindem et al. 2011; Garrison et al. 2015). However, such data has only been suggested for hop tests, and comparable asymmetry data during low-velocity movement screens is non-existent. Despite the usefulness of these results, many practitioners in the field may not have access to force plates. Therefore, we should never under-estimate the importance of a critical eye when it comes to assessing movement quality, a subjective concept that has been recognised as an integral piece of the screening jigsaw (Bishop et al. 2015). That being said, Atkins’ research

provides a useful insight into the rationale for using the overhead squat across multiple age groups in a youth sporting population.

Motion analysis has also been a common tool when aiming to delve deeper into the mechanics of this screen (Butler et al. 2010; Whiteside et al. 2014; Mauntel et al. 2015). Butler et al. (2010) undertook a biomechanical analysis of the overhead squat whereby peak joint angles and joint moments were calculated for 28 subjects (scored subjectively via the FMS grading criteria). Significant differences ($p < 0.01$) were seen between groups (those who scored one, two, and three) for peak knee and hip flexion and knee extension moment, but not for dorsiflexion (Butler et al. 2010), perhaps suggesting a ‘hip hinge’ strategy was adopted by those who scored better. However, it is unclear whether such differences were a result of reduced joint range of motion or whether alternative coaching cues could have solved the movement competency issue. More recently, Whiteside et al. (2014) compared motion analysis with real-time grading for the overhead squat screen. The usual kinematic parameters such as spinal and knee alignment, depth of squat, and torso to tibia positioning were graded subjectively by real-time ‘raters’. Additionally, kinematic equivalents were created by the motion analysis software. For example, in order to establish whether the femur went below parallel, the long axis of the femur was aligned with the transverse plane axis in a software program (Whiteside et al. 2014). Results indicated an 18.2% level of agreement between real-time and motion analysis when interpreting movement quality. It has been suggested that raters are required to survey multiple areas when screening in real-time, which may increase the probability of inaccuracies during subjective analysis. This is supported by Banskota et al. (2008) who reported real-time visual kinematic errors between 10–15°, which may suggest that grading the overhead squat without accompanying technology may not be reliable when identifying kinematic dysfunctions.

Considering its popularity in the field as a generic screening protocol, little research appears to exist in relation to muscle activity (EMG) during the overhead squat. It has been reported that when subjects exhibit medial knee displacement (knee valgus), this compensation is accompanied by significantly reduced ($p < 0.001$) dorsiflexion and increased adductor activation ($p = 0.02$) (Bell et al. 2012). This is further supported by Macrum et al. (2012) who used a 12° ‘wedge’ to purposefully restrict ankle dorsiflexion during a squat pattern (compared to a no wedge condition).

There was a significant increase in medial knee displacement ($p < 0.001$; effect size = 2.92) and significant decrease in vastus lateralis and vastus medialis oblique activation ($p < 0.05$; effect size range = 0.2–0.33) during the wedge condition. Essentially, it was concluded that reduced ankle range of motion resulted in lower quadriceps activity and increased compensations medially at the knee joint, highlighting the importance of adequate dorsiflexion.

In conclusion, the aforementioned evidence would indicate that the use of expensive laboratory equipment (force plates, motion analysis, and EMG) is favourable to obtain accurate kinematic, kinetic, and muscle activity information for the overhead squat. However, it must be acknowledged that few practitioners will have access to these types of equipment; therefore, alternative methods of assessing movement quality should also be considered. Numerous smart phone/tablet 'apps' such as Coach's Eye, Hudl Technique, and even the standard video recording function on these devices will almost certainly enhance a coach's capacity to extract reliable information from this assessment. Therefore, in order for practitioners to be able to interpret their findings (regardless of the methods employed), it would be useful to understand common dysfunctions associated with this screen. Example pictures of a desirable overhead squat pattern (Figures 13.1–13.3) and common movement dysfunctions (Figures 13.4–13.9) have been included in line with previous suggestions (Bishop et al. 2016).

FIGURE 13.1 Overhead squat (anterior view).

FIGURE 13.2 Overhead squat (lateral view).

FIGURE 13.3 Overhead squat (posterior view).

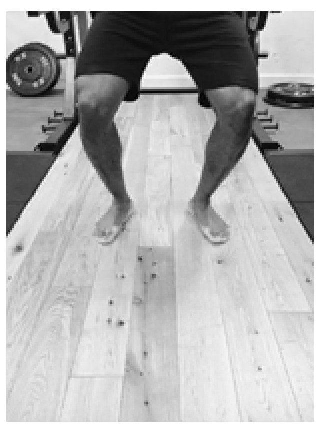


FIGURE 13.4 External rotation of the feet.

FIGURE 13.5 Knee valgus.

FIGURE 13.6 Excessive forward lean.

FIGURE 13.7 Lower back arching.

FIGURE 13.8 Lower back rounding.

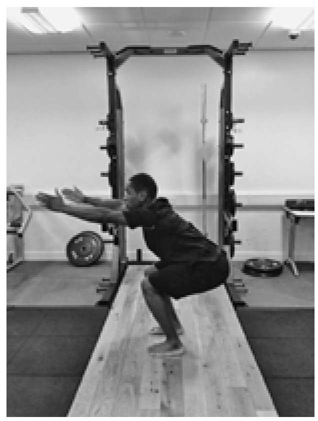


FIGURE 13.9 Arms fall forward.

Regardless of the methods employed to assess this screen, athletes should be instructed to perform the overhead squat identically each time, thus enhancing the reliability of extracting any relevant information pertaining to movement competency. Suggested set up procedures have been proposed by Bishop et al. (2016) and can be seen in Table 13.1.

SINGLE LEG SQUAT

The single leg squat (SLS) has been the subject of numerous research studies, predominantly in the rehabilitation field if we are to take note of where the majority of literature has been published. The main focus of research has been on muscle activation levels (Zeller et al. 2003; DiStefano et al. 2009), its ability to identify hip abductor weakness (Beutler et al. 2002; Noehren et al. 2012; Mauntel et al. 2014; Macadam et al. 2015), and

differentiated kinematics between injured and non-injured populations (Levinger et al. 2007; Willy et al. 2012; Herrington, 2014; Trulsson et al. 2015).

TABLE 13.1 Suggested instructions for the overhead squat assessment (adapted from Bishop et al. 2016)

Instruction	*Rationale for instruction*
Set feet hip-width apart at 12 o'clock	Narrow foot position, set straight ahead will require optimal levels of dorsiflexion (20–30°) (Clark and Lucett 2010), to avoid compensations at the foot/ankle complex. It should be noted that this may not be considered optimal foot positioning for loaded squat training, rather it is designed to identify potential restrictions in ankle range of motion earlier on in the squat pattern, if they exist. Furthermore, external rotation at the feet may also allow for more depth by virtue of additional range being 'provided' at the hip joint. As such, straight feet are recommended to get an indication of mobility in the squat pattern with respect to both the ankle and hips.
Shoulders in full flexion	Optimal shoulder flexion has been reported to be 180° (Howe and Blagrove 2015) and coaches should instruct athletes to 'raise their arms above their head' and maintain this position throughout the screen. Coaches are looking to see if the arms are a continuation of straight spinal alignment throughout the available range of motion.
Keep head neutral/eyes looking forward	It has been suggested that this falls in line with optimal squatting technique (Myer et al. 2014). If the athlete is allowed to flex at the neck (look down) this may make it harder to visually distinguish compensations at the shoulder joint such as the arms falling forward.
Ask athlete to remove footwear	In order to standardise testing procedures, all athletes should remove footwear so that no 'assistance' can be provided for any reduced ankle mobility.
Ask athlete to squat as deep as possible	This should encourage athletes to challenge their depth in the squat pattern. Some compensations such as knee valgus and excessive forward lean may not be apparent at shallow depths, therefore it is in the interest of the coach to determine if full range of motion is available and whether the athlete has the strength to maintain form throughout the available range. Furthermore, visual demonstrations have been suggested as a more advantageous strategy to enhance motor learning (Horn et al. 2010), therefore the author suggests that no demonstrations are provided as this may affect outcomes.

With muscle activation (measured via EMG) typically reported as a percentage of maximal voluntary isometric contraction (MVIC), gluteus maximus activation would appear to range from 35–81% (Zeller et al. 2003; Boudreau et al. 2009; DiStefano et al. 2009) in healthy populations whilst subjects portraying injury symptoms or faulty movement mechanics (knee

valgus) have noted muscle activation as low as 17–20% (Nakagawa et al. 2012; Mauntel et al. 2014). Similar trends can be seen for the gluteus medius muscle with activation levels reported between 30–77% in healthy subjects (Zeller et al. 2003; Boudreau et al. 2009; DiStefano et al. 2009), but as low as 18% in subjects with patella-femoral pain syndrome (PFPS) (Nakagawa et al. 2012). Despite the notable contributions from the gluteal complex, it would appear that the highest muscle activation is seen in the quadriceps, with muscle activation ranging from 75–116% (Zeller et al. 2003; Mauntel et al. 2014).

Further to this, research has demonstrated a capacity for the SLS to portray significant differences between healthy and injury-symptomatic subjects when assessed using more objective measures. Munro et al. (2012) used two-dimensional video analysis to assess the reliability of frontal plane projection angle (FPPA) of the knee joint during the single leg squat. Reflective markers were positioned in the centre of the knee and ankle joints and on the proximal thigh in line with the anterior superior iliac spine, allowing subsequent analysis to quantify the angle. Between-session data reported strong levels of reliability with intra-class correlation coefficients of 0.72–0.88 for the assessment of FPPA. Consequently, results from research using similar methods can likely be interpreted with confidence. Earlier research from Levinger et al. (2007) used a single digital camera and reflective markers to quantify the same metric. Results identified a significant difference ($p = 0.019$) between healthy subjects who reported a mean FPPA of 7.79 ± 4.42° during the SLS compared to 11.75 ± 3.61° in subjects demonstrating PFPS. This was further supported by Herrington (2014) who used similar procedures and reported a significant difference ($p < 0.01$) in mean knee valgus angles between healthy subjects (8.4 ± 5.1°) and those reporting PFPS (16.8 ± 5.4°).

In conclusion, the SLS has established the involvement of the gluteal complex, supported the hypothesis that there is an association with knee valgus and FPPA, and differentiated between subjects with and without injury symptoms. Furthermore, the use of a single digital camera would appear to suffice when quantifying compensations at the knee joint; thus, the use of smart phones/tablets can again be considered by practitioners to enhance the accuracy of subsequent analysis. Where practitioners in the field may struggle is using reflective markers (often associated with laboratory-based analysis). However, use of apps such as Coach’s Eye and

Hudl Technique will allow for lines to be drawn/angles to be calculated at relevant points within the video capture, allowing for increased accuracy during subjective kinematic analysis. With this in mind, example pictures have been provided demonstrating desirable form (Figure 13.10) and common compensations (Figures 13.11–13.15) associated with this screen.

FIGURE 13.10 Single leg squat.

FIGURE 13.11 Knee valgus.

FIGURE 13.12 Hip hike.

FIGURE 13.13 Hip drop.

FIGURE 13.14 Inward trunk rotation.

FIGURE 13.15 Outward trunk rotation.

Finally, just as described for the overhead squat, universal testing procedures should always be adhered to where possible, and suggestions for the SLS are summarised in Table 13.2.

FUNCTIONAL MOVEMENT SCREEN

The Functional Movement Screen (FMS) has received much attention in the literature in recent years (Cook et al. 2010; Frost et al. 2012; Fox et al. 2013; Frost et al. 2014; Kazman et al. 2014). The FMS consists of seven individual tests (deep [overhead] squat, inline lunge, hurdle step, active straight leg raise, shoulder mobility, trunk stability push-up, and rotary stability) that provide an overall impression of movement quality (Cook et al. 2010). With that in mind, one of its creators has previously suggested that if athletes are unable to perform such movement, then uncovering this information may assist with reducing injuries and improving athletic performance (Cook 2004). Furthermore, the numerical grading system (zero to three) means that comparative data analysis is easy for practitioners to run; thus, an attempt to establish its relationship with athletic performance and injury risk has been a popular stream of investigation.

TABLE 13.2 Suggested instructions for the single leg squat assessment

Instruction	*Rationale for instruction*
Keep hands placed on hips	Allowing arms to be outstretched will naturally counteract an athlete's centre of mass, allowing them to go deeper. Keeping hands fixed to hips will help to standardise testing procedures and remove any 'assistance' from an outstretched arm position.

Position non-stance foot parallel to stance foot	Stretching the non-stance leg in front as seen in the 'pistol squat' exercise will also aid technique. Interpretation of SLS quality has a major focus on hip alignment; thus, keeping the hovering foot raised just off the ground should help to determine if there is a true hike/drop in this region, due to the hips starting as close to neutral as possible (should this be the case before any movement is initiated).
Point stance foot straight ahead	External rotation at the foot may have an unwanted effect on the knee joint. The tibia inserts into both the knee and ankle joints and any external rotation of the foot (and therefore tibia) may encourage internal rotation of the femur, potentially increasing the likelihood of knee valgus.
Ask athlete to remove footwear	In order to standardise testing procedures, all athletes should remove footwear so that no 'assistance' can be provided for any reduced ankle mobility.
Ask athlete to squat to as deep as possible	This should encourage athletes to challenge their range of motion and strength in this pattern. However, the neuromuscular demand for this test is greater than the overhead squat and coaches should be aware of asking athletes to squat 'as deep as possible' for any athlete showing signs or symptoms of injury, particularly at the knee joint.

Parchmann and McBride (2011) investigated the relationship between the FMS and maximal lower body strength (1RM back squat) with 10m and 20m sprints, agility t-test, and vertical jump height in 25 NCAA Division 1 college athletes. Results revealed no significant correlations between the sum of scores in the FMS and any of the performance tests. In contrast, the relationship between 1RM squat strength and 10m (r = –0.81), 20m (r = –0.87), vertical jump (r = 0.87), and agility t-test (r = –0.76) provides some evidence that maximal strength plays a pivotal role in an athlete's capacity to sprint, jump, and change direction.

The lack of association with physical performance is further supported by the work of Okada et al. (2011) who investigated the relationship between the FMS, core stability, and measures of performance. Twenty-eight healthy subjects performed spinal flexion/extension and side plank endurance tests for the core musculature, in addition to an overhead medicine ball toss and single leg squat for the performance-orientated assessments. There were no significant correlations between the FMS and either core stability or performance-based tests (Okada et al. 2011), again indicating a distinct lack of relationship. However, it should be

acknowledged that the single leg squat could be considered a questionable choice when labelled as a ‘performance test’. Finally, Fox et al. (2013) reported normative FMS scores in male Gaelic field sports and noted no difference between elite and sub-elite athletes (mean score = 15.8 ± 1.58 vs. 15.34 ± 1.31, respectively). The results from Fox et al. (2013) indicate that the FMS may not be able to differentiate between athletes of varying performance levels, which may suggest it is too generic to use on an athlete population.

Similar to any attempted research with athletic performance, its association with injury risk has also been investigated. Any such studies have been required to create a ‘cut-off’ point during statistical analysis in order to determine the sum score’s capacity to predict injury. Typically, a score of ≤ 14 has been used as a threshold, most likely because it provides an indication of an average score of two across all tests. Naturally, there are flaws with such an assumption (discussed later). O’Connor et al. (2011) used the FMS in an attempt to predict injuries in 874 marine officers. Subjects were divided into either long (68 days, *N* = 427) or short (38 days, *N* = 447) training cycles, and injuries were monitored throughout. Regardless of training cycle, FMS scores were categorised into ≤ 14, 15–17, and ≥ 18, and results can be seen in Table 13.3.

The results from O’Connor’s study indicate that marine officers who scored ≤ 14 were more likely to get injured when compared to those who scored in the other two brackets. However, it must be noted that the identified imbalances (as measured by the scores of ≤ 14) were not ‘treated’ within the respective training cycles; therefore, it is impossible to know whether these injuries could have been prevented.

Chorba et al. (2010) assessed the ability of the FMS to determine injury risk in a female collegiate population (*n* = 38), with seven subjects reporting prior reconstructive surgery on their anterior cruciate ligament (ACL). Results identified 69% of subjects that scored ≤ 14 sustained an injury during the intervention period (pre-season) and a strong correlation (*r* = 0.76) was reported between this group and injury rates. However, what is perhaps more important is that the FMS was unable to differentiate between subjects with and without prior ACL trauma. With ACL injuries having been shown to alter movement patterns (Stergiou et al. 2007), a screening process that is unable to differentiate between subjects that have or have not had this type of injury may increase the risk of re-injury to an athlete, as

this aspect of the screening process could be missed. Specifically, the predominance of static tasks performed during the FMS may not have been challenging enough to determine functional limitations in athletes with a prior injury. This highlights the need for more dynamic forms of assessment that are reflective of speeds and forces experienced during sporting movements.

TABLE 13.3 Injury rates by cycle length in marine officers with differing FMS scores (adapted from O'Connor et al. 2011)

Cycle	*FMS score*	*N*	*Injured (%)*	*P*
Long Cycle	≤14	36	52.8*	0.001
	15–17	283	29.3	
	≥ 18	108	44.4	
Short Cycle	≤ 14	57	40.4*	0.015
	15–17	223	22.2	
	≥ 18	166	28.9	

Note: *Statistically significant compared to other FMS scoring brackets

Butler et al. (2011) investigated whether performance in physical fitness tests and the FMS were predictors of injury in 108 firefighters. The performance tests consisted of a sit and reach test, push-up test (maximum number performed in two minutes), pull-up test (until failure), 1.5 mile run, and a firefighter-specific 'tower test'. However, when the seven tests were assessed individually by way of regression analysis, the deep squat and push-up test together were the only two tests that were able to moderately predict injury (r = 0.330), whilst the sit and reach test was the only physiological variable that was a moderate predictor of injury (r = 0.218). With this in mind, these results should be interpreted with caution, as the sit and reach does not challenge joint mobility in specific areas of the kinetic chain and is unlikely to be used as either a 'performance test' or screening protocol in S&C practice.

Whilst there appears to be some evidence to the notion that FMS scores ≤ 14 may be associated with heightened injury risk, methodological issues and interpretation of results must be considered as part of the bigger picture. Furthermore, regardless of using the FMS to complement physical fitness

testing or identifying those at increased injury risk, some logistical considerations must be considered. Clifton et al. (2015) undertook off-season screening using the FMS protocol on 103 collegiate athletes, with the primary purpose of identifying if the deep squat test could predict overall FMS performance. Scores were categorised into low performers (< 2 for the deep squat screen; < 12 for sum FMS score) and high performers (≥ 2 for the deep squat; ≥ 12 for sum FMS score). Interestingly, subjects who scored 'low' on the deep squat screen also scored significantly lower ($p < 0.001$) on the FMS as a whole. Furthermore, the deep squat was positively correlated with FMS sum score ($r = 0.50$, $p < .001$), and although correlation does not dictate causation, it provides some indication that better movement quality from an overhead squat screen may be indicative of overall movement quality. Knowing that the overhead squat is effective at challenging the mobility of all key joints in the kinetic chain, it could be suggested that this test provides the most useful information out of any one screen from the FMS. It is not being suggested that the additional six screens are insignificant, more so that it is likely that useful information may be best extracted from each individual test, rather than a composite score. This is supported by Li et al. (2015) who used exploratory factor analysis to highlight that collectively, the seven tests had low internal consistency which could be somewhat overcome by placing a greater emphasis on individual test scores rather than the sum. Practically speaking, a sum score of 19 could be obtained with maximum scoring for all tests apart from a one on a single test. As such, if that test were to be ignored (by virtue of using the sum score as a guide alone), this may be a potential risk factor for injury.

Furthermore, many of these movements (or similar) will continually be monitored each time athletes step into the weight room by virtue of squats, lunges, presses, and rotational exercises (and their associated variations) being frequently programmed for athletes. Therefore, monitoring technique development for these movement patterns can likely be done continuously during training sessions. It should also be emphasised that the chosen movements in the FMS (whether used as a screen or monitored in training) should be performed with optimal technique as many will form the foundation for key qualities such as strength and power to be built upon safely. Additional consideration must also be given to logistics in the field. Time is a crucial factor in the sporting profession, with the S&C coach

often asked to produce results in a time-constrained, high-pressure environment. The reality is that seven tests (five of which must be performed on both limbs) if done properly, will take about 10 to 15 minutes to complete. This does not make for a particularly practical use of time when working with large groups of athletes. In addition, the FMS is typically graded in real-time and the previous information in this chapter from Whiteside et al. (2014) and Banskota et al. (2008) would also indicate that such subjective measures may require further support to enhance the reliability of the outcomes. When all things are considered, it is perhaps practical to suggest that alternative screening tests may assist coaches in identifying movement compensations in a more time-efficient manner. Furthermore, high-velocity screens may at least partially replicate the forces experienced in a sporting situation (Bishop et al. 2015), justifying their place in a screening battery.

LANDING ERROR SCORING SYSTEM

The Landing Error Scoring System (LESS) is a screening tool that aims to subjectively assess an athlete’s risk of suffering a non-contact ACL injury from a similar method as a traditional drop jump (Padua et al. 2009; Padua et al. 2011; Padua et al. 2012; Smith et al. 2012). The key difference is that the athlete is required to jump forward (off a 30cm box) 50% of their height and then jump vertically as high as possible, as opposed to ‘stepping off’ the box as per the drop jump method. Two cameras are used from the sagittal and frontal plane, views that allow practitioners to grade an athlete’s landing mechanics against a set of pre-determined criteria (Padua et al. 2009). Originally, a 17-point scale was created that addressed potential kinematic compensations at the ankles, knees, hips, and torso. However, it has been deemed too time consuming (Padua et al. 2009); thus, a modified version was validated in 2011 (Padua et al. 2011). The modified version has ten points to consider for grading and has reported acceptable reliability when graded in real-time (intraclass correlation coefficient (ICC) = 0.72–0.81) (Padua et al. 2011), compared to the full 17-point scale with accompanying video analysis (ICC = 0.84) (Padua et al. 2009). Tables 13.4 and 13.5 show the operational definitions and grading criteria, respectively.

One of the original LESS studies by Padua et al. (2009) investigated the reliability of this protocol on 2,691 army cadets from US military

academies. As previously mentioned, strong ICC values were reported (0.84), but scores were also placed into brackets depending on outcome. A score of ≤ 4 was deemed 'excellent' whilst > 6 was considered 'poor'. There were considerable differences between male and female cadet scores, with 29% of males and 14% of females scoring in the excellent category and 23% of males and 36% of females scoring poorly (Padua et al. 2009). Poor scores were associated with higher levels of knee valgus, hip adduction, and increased hip/knee internal rotation. Perhaps more importantly, the LESS was able to distinguish between subjects who had previously suffered an ACL injury and those who had not, an outcome that has been noted again more recently (Bell et al. 2014).

TABLE 13.4 Operational definitions for the modified LESS sheet (adapted from Padua et al. 2011)

LESS criteria	*Operational definition*	*Rater view*
Stance width	Abnormally wide or narrow stance during landing, they receive an error (+1)	Front
Foot-rotation position	Moderate amount of external rotation or internal rotation, they receive an error (+1)	Front
Initial foot-contact symmetry	If one foot lands before the other or there is alternating heel-to-toe/toe-to-heel landing mechanics, they receive an error (+1)	Front
Knee valgus	Small amount of knee valgus (+1) Large amount of knee valgus (+2)	Front
Lateral trunk flexion	If trunk is not perfectly vertical in frontal plane, they receive an error (+1)	Front
Initial landing of feet	If subject lands heel-to-toe or flat-footed, they receive an error (+1)	Side
Amount of knee flexion	Small amount of knee flexion displacement (+1) Average amount of knee flexion displacement (+2)	Side
Amount of trunk flexion	Small amount of trunk flexion displacement (+1) Average amount of trunk flexion displacement (+2)	Side
Total joint displacement in sagittal plane	Large displacement of trunk & knees = 'soft' (0) Average displacement of trunk & knees = 'average' (+1)	Side

	Small displacement of trunk & knees = 'stiff' (+2)	
Overall impression	Soft landing with no frontal plane motion at the knee = 'excellent' (0) Stiff landing with large frontal plane motion at the knee = 'poor' (+2) All other criteria rates 'average' (+1)	N/A

Additional normative values for the LESS have been reported elsewhere in the research (Padua et al. 2012; Smith et al. 2012). Smith et al. (2012) reported mean LESS scores of 4.42–5.53 in healthy high school and college athletes versus 4.70–5.91 in high school and college athletes who had previous ACL injuries. Padua et al. (2012) undertook two ACL injury prevention programs on youth soccer players consisting of flexibility, balance, strength, plyometrics, and agility training for either a short (three months; *n* = 33) or long (nine months; *n* = 51) intervention period. Furthermore, a 'retention' LESS test was undertaken three months post-training to determine the effectiveness of each intervention. Pre-intervention LESS scores were 5.17 and 5.70 for the three- and nine-month groups, respectively. Post-intervention LESS scores improved to 3.39 and 4.07, demonstrating how motor control in landing mechanics improved from both interventions. However, the three-month group portrayed a mean retention score of 4.69 whereas the nine-month intervention group's mean score was reported to be 4.20 (Padua et al. 2012). The authors deduced that three months may not be a long enough period to retain significant improvements in landing mechanics for high school and college athletes. Although speculative, it is logical to assume that athletes with a lower training age (such as high school athletes) will require longer for desired movement competency to be truly engrained.

TABLE 13.5 The Landing Error Scoring System (LESS) score sheet for the modified version of the LESS (adapted from Padua et al. 2011)

Observing from the front	*Observing from the side*
1. Stance width ~ Normal (0) ~ Wide (1) ~ Narrow (1)	6. Initial landing of feet ~ Toe-to-heel (0) ~ Heel-to-toe (1) ~ Flat feet (1)
2. Maximum foot rotation position	7. Amount of knee flexion displacement

~ Normal (0) ~ Moderately externally rotated (1) ~ Slightly internally rotated (1)	~ Large (0) ~ Average (1) ~ Small (2)
3. Initial foot contact ~ Symmetric (0) ~ Not symmetric (1)	8. Amount of trunk flexion displacement ~ Large (0) ~ Average (1) ~ Small (2)
4. Maximum knee valgus angle ~ None (0) ~ Small (1) ~ Large (2)	9. Total joint displacement (sagittal plane) ~ Soft (0) ~ Average (1) ~ Stiff (2)
5. Trunk lateral flexion ~ None (0) ~ Small to moderate (1)	10. Overall impression ~ Excellent (0) ~ Average (1) ~ Poor (2)
TOTAL SCORE =	

In light of the evidence, the LESS would appear to be a reliable method for assessing landing mechanics, and has been shown to differentiate between subjects who have and have not suffered ACL trauma. Normative scores for this assessment would appear to fall within a range of ~4–6, with a key emphasis on trying to reduce this figure should it be continually used as part of a screening battery. Despite the information portrayed in favour of the LESS, results are subjective, which although favourable to practitioners in the field, is likely to exhibit error with unfamiliar raters. Similar to the single leg squat, quantifying objective measures such as knee valgus or FPPA could be considered to enhance this screen, especially as video analysis is already a pre-requisite for test requirements and has been used across comparable landing tasks (Comfort et al. 2016) such as the drop jump. Finally, the LESS grades mechanics from only a single landing, and a test that interprets movement quality during repeated jumping actions may be able to identify landing dysfunctions that the LESS cannot.

TUCK JUMP ASSESSMENT

The tuck jump assessment (TJA) requires subjects to perform tuck jumps on the spot repeatedly for ten seconds (Myer et al. 2011). This repeated nature may allow coaches to observe flaws in landing mechanics during a higher

intensity plyometric exercise when compared to the LESS (Myer et al. 2011; Bishop et al. 2015). In addition, although the test only occurs over a ten-second timeframe, the repeated nature may induce some level of fatigue, a concept that is unlikely to play a part in other high-velocity screens. As per the LESS, a grading criterion was created by Myer et al. (2011) and can be viewed in Table 13.6.

One of the first priorities when using any testing protocol is to assess its reliability in order to understand whether it can be repeatedly used (Bishop et al. 2015) and can detect true changes (Turner et al. 2015). Reliability of the TJA has been researched by Herrington et al. (2013) and Read et al. (2015). Herrington et al. (2013) used two raters to independently grade ten adult subjects and showed that the average agreement was 93%, with 100% agreement across five of the individual criteria. Read et al. (2015) screened 25 pre- and 25 post-peak height velocity elite youth soccer players with each player's score graded retrospectively across two different sessions. The TJA was deemed highly reliable (ICC = 0.88) but when each criterion was analysed individually, knee valgus was the only one that reached a substantial agreement between testing sessions across both groups (Read et al. 2015). These results indicate that although the TJA may be a reliable measure for screening landing mechanics, caution should be taken when interpreting the sum score.

TABLE 13.6 Grading criteria for the tuck jump assessment (adapted from Myer et al. 2011)

Tuck jump assessment	*Pre*	*Mid*	*Post*	*Comments*
Knee & thigh motion				
1. Lower extremity valgus at landing				
2. Thighs do not reach parallel (peak of jump)				
3. Thighs not equal side-to-side (during flight)				
Foot position during landing				
4. Foot placement not shoulder-width apart				
5. Foot placement not parallel (front to back)				
6. Foot contact timing not equal				
7. Excessive landing contact noise				
Plyometric technique				

8. Pause between jumps	________________________
9. Technique declines prior to ten seconds	________________________
10. Does not land in same foot-print (excessive in-flight motion)	________________________
Total score	

This is further supported by Lininger et al. (2015) who undertook an exploratory factor analysis of the TJA on college athletes. Previous literature from Myer et al. (2011) identified five risk factors that each of the ten grading criterion might fall into: ligament dominance, quadriceps dominance, leg dominance, trunk dominance, and technique perfection. Lininger's analysis investigated the internal structure of the TJA via a psychometric examination, and results indicated that fatigue, distal landing pattern, and proximal control accounted for 46% of the variance. With nearly half the variance accounted for by three factors not outlined by Myer's original suggestions, the authors suggested that the use of a sum score at the end the assessment may be questionable. Finally, Klugman et al. (2011) examined whether an in-season ten-week plyometric program improved TJA scores in 49 female high school soccer athletes. Subjects were split into intervention (n = 15) and control (n = 34) groups, but it was not specified how many sessions a week the intervention group performed; merely that they attended 95% of total training sessions. The intervention group showed a slight improvement in TJA scores (pre = 5.4, post = 4.9). However, the control group who received no additional training other than their regular soccer practices also made comparable improvements (pre = 5.8, post = 5.0) (Klugman et al. 2011). It was suggested that there may be a dose-response relationship from this type of training and that ten weeks may not have been enough to depict significant improvements in tuck jump performance. However, without knowing more specific details of the number of sessions undertaken, it is impossible to draw objective evaluations.

In conclusion, the evidence from Herrington et al. (2013) and Read et al. (2015) would suggest that the TJA is a reliable screening method; however, using the sum score may not provide as much value to the coach as was perhaps first intended. Lack of consistency between which grading criteria repeatedly present themselves and the suggested modifiable risk factors

would suggest that further research is almost certainly warranted with this screen. Furthermore, Myer et al. (2008) highlight the importance of an athlete’s neuromuscular control and suggested that the TJA has the capacity to repeatedly monitor this. Whilst this idea cannot be argued with, the practicalities of who to implement this with must be considered. Notable discrepancies in landing mechanics have been noted in the LESS from just a single landing, yet the repeated nature of the TJA will make this test a considerable progression. It is the advice of the author that coaches carefully consider whether an athlete is ready for such an advanced screening method. Perhaps the TJA would best be utilised as a progression from the LESS, with coaches incorporating it once all compensations have been rectified from a single landing.

So far, the high-velocity screens discussed have both been bilateral in nature. Jones et al. (2014) suggested that injuries occur in a multitude of ways such as cutting and side-stepping, both of which occur in a unilateral environment. With this in mind, it is suggested that a high-velocity unilateral screen will also provide practitioners with some useful information.

SINGLE LEG HOP

Hop tests have been the subject of numerous research studies in the rehabilitation setting (Barber et al. 1990; Noyes et al. 1991; Ross et al. 2002; Reid et al. 2007; Munro and Herrington, 2011; Rohman et al. 2015), with a particular emphasis on their ability to differentiate performance between those who have and have not had ACL trauma and provide quantifiable data pertaining to return to activity post-ACL injury. Unlike many of the aforementioned screening methods, hop tests would not appear to have a specific grading criterion; moreover, their use appears to have been associated with asymmetry scores between limbs. These differences are often used to calculate a Limb Symmetry Index (LSI) score (see Equation 13.1), which acts as a percentage of symmetry between limbs on the associated test (Barber et al. 1990; Garrison et al. 2015).

Equation 13.1

Limb Symmetry Index (%) = (Involved limb ÷ Uninvolved limb) × 100

The single leg hop (SLH) is performed for maximal distance achieved on one limb and requires no expensive equipment, thus, it can be used by coaches at all levels in the industry. The simplicity associated with the test is undoubtedly a reason as to its common inclusion in a research setting. Rohman et al. (2015) monitored changes in LSI scores for ten functional tests (including the SLH) in 122 subjects during the ACL rehabilitation process. The authors described how it was deemed necessary for subjects to demonstrate 90% symmetry between limbs on all tests to be considered 'rehabilitated'. The SLH was first conducted 158 days post-surgery and demonstrated LSI scores of 78.2%, with the 90% threshold being reached 81 days later (Rohman et al. 2015). Although no specific details of the rehabilitation process were provided, it is useful to note that subjects reached the required symmetry scores eight months post-surgery. However, this 90% threshold has not always been suggested as the benchmark for symmetry between limbs.

Earlier research from Barber et al. (1990) undertook a quantitative comparison of healthy subjects (n = 93) and those showing positive ACL symptoms (but who had not had surgery) (n = 35). Mean asymmetry scores never went higher than 5% in the healthy subjects, whereas the ACL group showed significantly greater (p = 0.001) asymmetries of 18% between limbs. Interestingly, ~92% of the healthy population reported LSI scores ≥ 85%, which led authors to suggest that this was an acceptable asymmetry threshold for healthy subjects. This has been further supported by Noyes et al. (1991) who also investigated lower body asymmetries determined by hop tests post-ACL injuries. Sixty-seven patients (male = 40; female = 27) performed the SLH, the triple hop for distance, crossover hop for distance, and 6m timed hop as methods for determining asymmetry levels. With abnormal LSI scores considered to be below 85%, the SLH showed 52% of subjects demonstrated greater imbalances than the suggested threshold and 49% showed greater asymmetries during the timed hop also (Noyes et al. 1991). It was concluded that hop tests offer a simple method for determining lower limb functional limitations and should be used in conjunction with other tests to complete the screening picture. Finally, further evidence is offered by Grindem et al. (2011) who used the SLH (and

the triple hop, crossover hop, and 6m timed hop) as predictors of function in 91 subjects with an ACL injury. One year after diagnosis, the SLH was the only test able to detect asymmetries > 15% with a mean LSI of 83.6% in the ACL group (Grindem et al. 2011). Consequently, this led the authors to suggest that practitioners should use the SLH specifically as an assessment for lower limb function when returning from knee injury.

In conclusion, it would appear from the literature that the SLH is a viable method for determining inter-limb asymmetries, particularly for those who may be returning from injury. Despite its efficacy for injured populations, it is still suggested that the SLH is used for non-injured and athletic populations as a simple and effective screen for monitoring inter-limb differences. Considering a grading criterion does not currently exist for this test, it is prudent to use the LSI as a measure of determining such differences during a unilateral, high-velocity screen, and thus providing coaches with a tangible outcome to inform their practice. Should kinematic information wish to be investigated for this screen, then video analysis is required and, once again, objective information pertaining to knee valgus and FPPA could be considered if resources allow. If video analysis is used without accompanying objective measures, practitioners should consider focusing on knee/hip alignment and torso compensations in order to determine successful landing technique. Although different tests, the associated compensations often seen during the SLS test (Figures 13.11–13.15) may provide a useful starting point when subjectively interpreting movement competency during this screen.

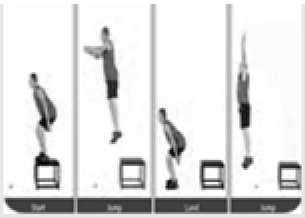
PUTTING A SCREENING PACKAGE TOGETHER

It is clear from the aforementioned evidence that the popular methods of assessing movement (overhead squat, FMS) require further support if coaches are to fully understand an athlete's movement profile. Therefore, high-velocity screens and methods for determining asymmetries are likely useful methods that will show movement information that the former cannot account for. However, it must be acknowledged that not all coaches will have access to the equipment needed to optimise the reliability of some of the testing procedures. With this in mind, it would be useful for coaches to have alternative options for screening movement so that some useful information can be obtained from the process. It should be understood,

however, that if the most reliable methods cannot be adhered to (such as using force plates and/or motion analysis), then some degree of error will likely accompany a coach's interpretation of the results. Whilst this is far from perfect, it is also most likely unavoidable and, provided this is accepted by the coach, the margin for error will most likely reduce with continued practice. Therefore, 'gold', 'silver', and 'bronze' packages have been suggested when screening movement (see Table 13.7) and methods can be chosen to suit each practitioner's situation. It is important to recognise that the screens themselves do not change between packages, rather the methods of analysis. The screens have been selected based off the aforementioned information presented in this chapter. In addition, it is the suggestion of the author that bilateral and unilateral screens under both low- and high-velocity conditions may help to provide coaches with a more complete picture of movement quality than any one screen alone. However, practitioners are encouraged to remember that, as always, any system requires flexibility, and if a given test is not deemed appropriate for the population in question, then alternatives may be more appropriate.

TABLE 13.7 Proposed gold, silver, and bronze screening packages

	Gold	*Silver*	*Bronze*
Overhead squat 	Conducted on twin force plates to quantify vGRF 3-D motion analysis used to quantify kinematic information	Recorded using smart phone video analysis (e.g.: Coach's Eye) Assessed retrospectively	Assessed in real-time
Single leg squat 	3-D motion analysis used to quantify kinematic information EMG used to determine lower limb muscle activation	Recorded using smart phone video analysis (e.g.: Coach's Eye) Assessed retrospectively	Assessed in real-time
LESS	Conducted on twin force plates to quantify	Recorded using smart phone video analysis	Assessed in real-time

	landing forces 3-D motion analysis used to quantify kinematic information	(e.g.: Coach's Eye) Assessed retrospectively	
Single leg hop 	Conducted on a force plate to quantify landing forces 3-D motion analysis used to quantify kinematic information	Recorded using smart phone video analysis (e.g.: Coach's Eye) Assessed retrospectively	Assessed in real-time

Notes: LESS = Landing Error Scoring System, vGRF = vertical ground reaction force, EMG = electromyography

Naturally, the most accurate information from screening an athlete's movement will come from the gold package, due to the higher reliability associated with the accompanying data analysis. Whilst these procedures may be optimal, they are perhaps limited to those at the highest level of elite sport who either have the equipment themselves or the finances to align themselves to an institution that does. Even then, the time needed to set up EMG and motion analysis equipment, as an example, not to mention the time required to assess the screens afterwards, may not make the gold package the most practically viable in the field. For the silver package, the screens are still graded retrospectively, and thus the time needed post-procedures is still a requirement. However, due to recording from devices such as tablets or the coach's own recording equipment, procedures will take substantially less time to complete. This in itself holds the advantage of reducing the time the athlete is required to be there for testing, and thus any motivational issues affected by duration are likely to be less of a factor. Finally, with smart phones and tablets being so readily accessible to individuals these days, there is an argument to say that no coach should subject their screening methods to the 'error of real-time' and thus the bronze package. However, it still may have its place in the field. The margin for error when grading an athlete's movement is likely to be less as coaches become more established at using them. Therefore, if large squads are being assessed across any of the suggested screens and the pressure of

providing an immediate report (despite its potential inaccuracies) is at the forefront of a coach's agenda, then real-time grading may be the only option. Therefore, it is suggested that coaches grade each screen in real-time and retrospectively (to begin with) in an attempt to determine real-time accuracy. Once an acceptable level of agreement between the two methods is achieved, it may then be plausible to rely on the bronze package when time-efficient screening strategies are required.

CONCLUSION

Movement screening has been a vogue topic in recent years, with many debating its usefulness and applicability in the field. The lack of association between a range of movement-based tests (FMS) and performance may suggest that time could be better spent on other screens. However, an impression of movement quality is still almost certainly required, and as such, an assessment that challenges the major areas in the kinetic chain should provide this, justifying the overhead squat's position in a screening battery. As previously mentioned, the question of whether or not movement mechanics alter under load and/or speed must be considered. The LESS allows for both, and has the advantage of differentiating between subjects who have and have not experienced previous ACL trauma. Noting that many sporting actions occur unilaterally and are governed by a finite period of time, it makes sense to incorporate low- and high-velocity unilateral testing procedures to a screening battery. Consequently, the SLS and SLH may allow for these principles to be accounted for. Finally, it is always suggested that coaches should use whatever testing procedures best fits their practice. As such, a combination of bilateral and unilateral, low and high velocity, and using expensive equipment or real-time analysis should allow for the majority of coaches to gauge some useful information from their screening methods, regardless of the tests chosen.

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CHAPTER 14

Technical demands of strength training

Timothy J. Suchomel and Paul Comfort

INTRODUCTION

There are a number of factors to consider when implementing various forms of resistance training. While some factors such as the range of motion (ROM) performed, grip/stance, and load placement appear to be simplistic, others such as rest intervals, the direction that force is produced during exercises, and the intent of the movement, may be overlooked by practitioners. Thus, it is important for practitioners to develop an understanding of how each factor may affect potential training adaptations.

SECTION 1

EXERCISE TECHNIQUE

The technique used during a given exercise may largely alter the resultant training stimulus. Aside from an athlete's anthropometrics and training age, an exercise may be modified through changes in the ROM performed or the grip or stance adopted. The following paragraphs will discuss each of the outlined topics and how they may affect the adaptations elicited from training.

Range of motion

The ROM performed during an exercise describes the displacement of an athlete's body mass and/or the external load being lifted. When prescribing exercises for athletes, practitioners must focus on not only the ability of athlete to perform the exercise, but teaching them to perform each exercise through a ROM that permits the safe/correct execution of the exercise and will ultimately elicit the desired training adaptations. There is little debate that performing an exercise with proper technique is more important than the weight that may be lifted, however, some athletes may sacrifice the ROM performed in order to 'claim' that they lifted a heavier load. While this practice may only occur during 'max out' sessions, it should not be encouraged due to the training implications that may result from chronic use (e.g., training to failure mindset, developing poor technique habits, etc.). Instead, practitioners should promote the execution of exercises through the full ROM an athlete is able to perform, taking into account existing constraints such as the athlete's safety, flexibility, anthropometrics, and previous injuries that may hinder performance. By promoting such a practice, it is more likely that athletes will develop good training habits and positive training adaptations (e.g., increased strength and power, decreased injury risk, and improved/maintained ROM at the trained joints).

Squatting variations (e.g., back squat, front squat, goblet squat, etc.) are one of the most commonly prescribed exercises within resistance training programs. Regardless of the variation, the method in which it is performed

is often the subject of discussion when it comes to the desired ROM performed by athletes. Based on a practitioner's coaching philosophy, he or she may desire that their athletes perform full squats, parallel squats, half-squats, quarter-squats, or any combination of those previously listed. Certain squat depths may be considered by some to be 'more position specific' or 'safer'; however, the desired adaptations being sought may dictate the ROM performed. For example, previous research indicated that training with deep squats produced greater increases in quadriceps muscle cross-sectional area, lower extremity lean body mass, isometric knee extension strength, and jump height compared to shallow squats (Bloomquist et al., 2013). However, additional research indicated that training with quarter-squats produced greater improvements in sprint speed adaptations compared to full squats (Rhea et al., 2016).

It is important to note that the ROM performed during an exercise may dictate the activation of specific musculature, the training adaptations elicited, or the specificity to a sport movement. Previous research has indicated that greater gluteus maximus activation occurs during deeper squats, but found no differences between partial, parallel, or deep squats in vastus medialis, vastus lateralis, or biceps femoris activation (Caterisano et al., 2002). Similarly, Gorsuch et al. (2013) displayed that greater activation of the rectus femoris and erector spinae muscles was produced during parallel squats compared to partial squats, but noted no differences in biceps femoris or lateral gastrocnemius activation between squat variations. Additional literature supports these findings for the rectus femoris (Pereira et al., 2010), moreover, Bryanton et al. (2012) suggested that greater relative muscular effort was produced at greater squat depths for both hip and knee extensors.

While practitioners may have their opinions on what ROM should be performed, the decision to increase or decrease the ROM performed may be justified if the athlete is returning from injury or within specific training periods where larger or smaller volume-loads may be needed to elicit specific training adaptations. A further description of this will be discussed in Section 2 below.

Grip and stance variation

The grip or stance used during a given exercise may modify the training stimulus by changing the muscle activation patterns of the muscles being trained. For example, a wider grip during a bench press may increase the amount of activation of the sternoclavicular portion of the pectoralis major while decreasing the activation of the triceps brachii and anterior deltoid (Lehman, 2005, Barnett et al., 1995), however, such a grip may increase risk of shoulder injuries. Similarly, a wider squat stance may increase the activation of the adductor muscles (McCaw and Melrose, 1999), while a wider deadlift stance may increase vastus medialis, vastus lateralis, and tibialis anterior activation (Escamilla et al., 2002). Whether referring to a bench press, squat, or deadlift variation, different activation patterns may alter the extent to which the musculature is activated, which may ultimately affect potential architectural or neuromuscular adaptations. Previous literature has discussed this idea in greater detail for the bench press (Green and Comfort, 2007) and pull-up/lat pull-down (Leslie and Comfort, 2013) exercises.

Another grip consideration that has been previously discussed is the use of the ‘hook grip’ (Favre and Peterson, 2012). The hook grip is frequently used during the traditional weightlifting movements (e.g., snatch, clean and jerk) and their derivatives (e.g., clean pull from the floor, hang power snatch, mid-thigh pull, etc.). The idea behind the hook grip is that by wrapping additional fingers around the thumb, the athlete may prevent grip from being a limiting factor when it comes to the weight that can be lifted for single and multiple repetitions.

MECHANICAL DEMANDS OF EXERCISES

Force-velocity characteristics

The nature of each exercise partially determines the force-velocity characteristics that an athlete trains. For example, the back squat serves as a force-dominant exercise in which the primary goal is to develop muscular strength. In contrast, the jump squat is a velocity-dominant exercise that may be used to develop high-velocity/power characteristics. Cormie et al. (2010a) displayed that relatively weak men may improve their athletic performance by training with either a strength or ballistic training emphasis.

However, the authors also noted specific adaptations (i.e., greater strength vs. greater velocity adaptations) based on the type of training used. While it is important to emphasise high-force movements or high-velocity movements during certain periods of the training year, previous literature has promoted the use of combined loading (Haff and Nimphius, 2012) where athletes train and develop both the force and velocity sides of their force-velocity profile, although altering the primary focus periodically. Training in such a manner may ultimately lead to favorable adaptations in rate of force development (RFD) and power (Cormie et al., 2007). A recent review discussed how this method of training can be implemented using a sequenced progression of weightlifting derivatives (Suchomel et al., 2017).

Stretch-shortening cycle

The inclusion/exclusion of the stretch-shortening cycle (SSC) within a movement may impact the training stimulus an athlete receives. The SSC may allow for the activation of the stretch-reflex, optimisation of length-tension muscle factors, optimisation of muscle activation, and the concentric muscle action beginning at a higher force output (Aagaard et al., 2000, Komi, 2000, Komi, 1986, Cormie et al., 2010b). By using the SSC, an athlete may produce greater magnitudes and rates of force production, potentially allowing for heavier loads to be lifted or a given load being lifted at a higher velocity. In contrast, movements that exclude the SSC may require unique neuromuscular demands. For example, an exercise performed using a static start position may require a greater RFD compared to a movement that includes the SSC because an athlete must overcome the inertia of the training load from a dead-stop position compared to having developed a given magnitude of force previously. This has been observed in research that examined weightlifting derivatives (Comfort et al., 2011b, Comfort et al., 2011a). The inclusion/exclusion of the SSC may place varying demands on athletes, and thus, practitioners should consider each athlete’s sport/event when programming exercises to allow for maximum transfer of training.

Load placement

Similar to the ROM discussed above, the placement of the load during different exercise variations (e.g., front squat vs. back squat) may modify the activation of specific musculature. One study indicated that the front squat produced greater vastus lateralis activation during the ascending phase and entire movement, while the back squat produced greater semitendinosus activation during the ascending phase (Yavuz et al., 2015). In contrast, two other studies reported no differences in muscle activation between the front squat and back squat (Gullett et al., 2009, Contreras et al., 2016a, Yavuz et al., 2015). Additional research demonstrated that greater peak force, velocity, and power were achieved using a hexagonal bar deadlift compared to a traditional deadlift (Swinton et al., 2011).

While the previous example discusses exercises that are typically used for strength development, similar results have been shown with ballistic jumping movements. Previous research discussed the acute kinetic and kinematic differences between the jump squat and hexagonal bar jump (Swinton et al., 2012). Their results indicated that the hexagonal bar jump produced greater force, RFD, and jump heights at several different loads. Both studies by Swinton et al. (2011, 2012) noted that the differences displayed may have been due to more favourable moment arms based on the load being closer to the lifter's centre of mass, ultimately allowing for more efficient vertical force production.

Force production vectors

Muscular strength has been defined as the ability to produce force against an external resistance; however, when it comes to exercise selection, the direction in which the force is produced may alter an athlete's training outcomes. Recent research has examined the effects of training with exercises that emphasise more vertical force vectors compared to horizontal (Contreras et al., 2016b) or unilateral-multidirectional (Gonzalo-Skok et al., 2016). Contreras et al. (2016b) indicated that adolescent rugby and rowing athletes who trained with either the front squat or barbell hip thrust for six weeks demonstrated specific force vector adaptations. Specifically, those who trained with the front squat displayed greater improvements in the vertical jump, while the hip thrust group displayed greater improvements in the horizontal jump and 10m and 20m sprint times. Similarly, Gonzalo-Skok et al. (2016) indicated that amateur/semiprofessional team-sport

athletes who trained with squats produced greater unilateral and bilateral vertical jump and 25m sprint adaptations compared to those who trained with unilateral-multidirectional versapulley. In addition, those who trained using the versapulley produced greater improvements in lateral and horizontal jumps and change of direction tasks. Considering the above results, practitioners may note that the application of force during various exercises may produce specific adaptations. DeWeese et al. (2016) discussed this idea regarding resistance training practices for developing sprint speed. Although the above studies contradicted each other with what training method produced superior results, it is important that practitioners understand the orientation of the athlete when they are generating force.

Ballistic and non-ballistic exercises

The nature of the exercise(s) performed may result in a different training stimulus experienced by the athlete based on the intent of the movement. As noted above and in Chapter 2, this may include modifications in the force-velocity characteristics of the exercise. Previous work by Lake et al. (2012) and Newton et al. (1996) has highlighted the differences between lower and upper body exercises performed in a ballistic manner (i.e., acceleration throughout the entire movement) and exercises performed quickly (i.e., intentionally fast with a negative acceleration at the end of the movement). Taken together, these studies indicated that exercises performed in a ballistic manner produced greater force, velocity, power, and muscle activation compared to the same exercises performed quickly.

Practitioners may choose from a variety of ballistic exercises that may provide an effective training stimulus. Regarding the development of lower body explosive strength, the exercises that first come to mind may be the weightlifting movements and their derivatives due to their ability to improve force-velocity characteristics to a greater extent compared to other training methods (Hoffman et al., 2004, Tricoli et al., 2005, Otto III et al., 2012, Teo et al., 2016, Arabatzi and Kellis, 2012, Chaouachi et al., 2014, Channell and Barfield, 2008). This is likely due to movement specificity, but also the ability to accelerate a moderate-heavy load in a jumping movement with ballistic intent. Greater detail on how practitioners can use weightlifting movements to enhance sport performance will be covered in Chapter 15. While weightlifting movements provide an effective ballistic

training stimulus, it should be noted that exercises like the jump squat (Cormie et al., 2010a), kettlebell swing (Lake and Lauder, 2012), and ballistic squat can also provide an effective training stimulus for the improvement of lower body explosive strength.

Regarding ballistic upper body exercises, practitioners may be more limited with their exercise selection. Typical upper body ballistic exercises may include the bench press throw, plyometric push-up, and medicine ball throw. Newton et al. (1996) indicated that a ballistic bench press throw may produce greater force, power, and muscle activation compared to a bench press performed quickly. The extent of these differences can be explained by the velocity of the movement throughout its completion. The previous study noted that the velocity of the ballistic bench press throw was accelerated throughout the entire movement whereas the traditional bench press decelerated at the end of the movement. Taking these results into account, the traditional bench press may serve as more of a foundational exercise to develop strength, while the bench press throw may be used to develop RFD and power characteristics (Soriano et al., 2016). Similarly, Vossen et al. (2000) indicated that plyometric push-ups result in greater improvements in strength and power compared to traditional push-ups.

As noted above, the ability of ballistic exercises to improve a strength/power training stimulus is well documented. An additional benefit of ballistic exercises may be their ability to be used as a potentiation stimulus, as noted by Maloney et al. (2014). Previous research indicated that ballistic, concentric-only half-squats produced a larger and faster potentiation effect compared to those performed in a non-ballistic manner (Suchomel et al., 2016c, Suchomel et al., 2016d). This may be due to the ability of ballistic exercises to recruit high threshold motor units (van Cutsem et al., 1998), which display greater potentiation compared to smaller lower threshold motor units (Hamada et al., 2000).

REST INTERVALS

Inter-set rest intervals

Previous literature has indicated that rest intervals as short as 30 seconds (Sheppard and Triplett, 2016) or one minute (Kraemer et al., 2002) may be

used to stimulate adaptations in muscle hypertrophy. While a greater metabolic demand may be present following high volume exercise sets (Gorostiaga et al., 2012, Gorostiaga et al., 2010), an athlete's ability to recover during a short rest interval is limited, and thus, their capacity to tolerate the same loads or heavier loads becomes diminished as the number of sets increases (de Salles et al., 2009, Buresh et al., 2009). This is likely due to decreased adensosine triphosphate (ATP), phosphocreatine (PCr), and glycogen concentrations as well as increases in lactate concentrations due to repetitive high volume sets (Gorostiaga et al., 2012, Gorostiaga et al., 2010). As noted in Chapter 4, shorter rest intervals may induce elevations in anabolic hormones such as growth hormone (Kraemer et al., 1990, Kraemer et al., 1993, Boroujerdi and Rahimi, 2008). However, shorter rest intervals may also produce greater elevations in cortisol (Kraemer et al., 1993, Rahimi et al., 2010a, Rahimi et al., 2010b, Buresh et al., 2009), which may ultimately attenuate the effect that growth hormone and possibly testosterone (Rahimi et al., 2011) have on muscle hypertrophy.

Despite previous recommendations, additional literature indicated that longer rest intervals (1.5–3 minutes) may produce superior muscle hypertrophy and strength adaptations compared to shorter inter-set rest intervals (0.5–1 minute) (Schoenfeld et al., 2016, Robinson et al., 1995). This may be due to a number of factors; however, one must consider not only the quantity of work, but the quality of work. For example, previous research indicated that subjects were unable to complete four sets of ten repetitions during the back squat with 70% 1RM and two minutes of inter-set rest (Oliver et al., 2016). In response to the failed sets, the authors noted that they decreased the load performed within the remaining sets, which likely decreased the overload placed on the athlete. Longer inter-set rest periods may allow for an athlete to replenish their ATP stores and lessen the metabolic fatigue experienced to a greater extent prior to a subsequent set compared to shorter rest periods. Ultimately, this may lead to a higher quality of work performed through the continued use of the prescribed loads, and possible increased loads, during all sets, potentially leading to greater physiological adaptations (e.g., work capacity and muscle cross-sectional area).

Collectively, it appears that while shorter rest intervals have the potential to produce a hypertrophic response, peak adaptations in trained individuals may be limited due to the loads that may be maintained over multiple

exercise sets. Moreover, if the ultimate goal is to increase the muscular power of the athlete, training with shorter rest intervals may result in an endurance effect, which may interfere with long-term hypertrophy adaptations (Hawley, 2009, Baar, 2006). It should be noted that if practitioners are concerned with the increase in the overall training time associated with longer inter-set rest intervals, they may consider short rest intervals within a set to spilt up and maintain the work performed. This approach to training, termed cluster set training (Haff et al., 2008), will be discussed in greater detail below.

Much of the existing literature suggests that longer rest intervals may produce superior adaptations in muscular strength and power. As mentioned above, Robinson et al. (1995) indicated that longer rest intervals (1.5–3 minutes) produced greater strength and power adaptations during a high-volume program. Additional research indicated that longer rest intervals (2.5–5 minutes) resulted in a greater volume of work to be performed during a workout (Willardson and Burkett, 2005, Willardson and Burkett, 2008), greater ability to train with heavier loads (Willardson and Burkett, 2006), and greater strength increases (de Salles et al., 2010, Pincivero et al., 1997, Robinson et al., 1995) compared to shorter rest intervals (0.5–2 minutes). While another study indicated that no statistical differences in strength gains were found between two and four minute rest intervals (Willardson and Burkett, 2008), those who trained using longer rest intervals produced a larger practical effect compared to those who trained with shorter rest intervals (i.e., Cohen's d = 2.96, very large vs. d = 1.96, large) (Hopkins, 2014). The discussed research is in line with previous rest interval recommendations for improving muscular strength and power (i.e., 2–5 minutes) (Sheppard and Triplett, 2016, Kraemer et al., 2002, de Salles et al., 2009). It should be noted that the range in rest interval length may exist due to the training age (Willardson and Burkett, 2008), fibre type composition of the athletes, and the loads implemented in training. Rest interval recommendations are summarised in Table 14.1.

Intra-set/inter-repetition rest intervals

A growing body of literature has investigated inter-repetition rest within a set of exercise. Specifically, research has examined the effect that cluster sets (Haff et al., 2008) have on kinetic, kinematic, and technique

characteristics during various repetition schemes. A cluster set may be defined as a traditional exercise set that is split into smaller sets of repetitions (i.e., clusters) that are separated by rest intervals. One of the first studies examining cluster sets investigated the effect of various set configurations (i.e., traditional, undulating, and cluster) on clean pull performance (Haff et al., 2003). Their results indicated that a cluster set configuration may result in greater barbell velocity and displacement and power-generating capacity across an entire set. A similar series of studies examined the effect of rest interval length between repetitions within several sets on various power clean performance variables (Hardee et al., 2013, Hardee et al., 2012b, Hardee et al., 2012a). Collectively, their results indicated that cluster set configurations using 20–40 seconds of rest between repetitions allowed the subjects to maintain power output, technique, and lower their perceived exertion.

TABLE 14.1 Rest interval length to achieve specific training goals. Rest interval length may vary based on the type of exercise, load, repetition scheme, and training status of the athlete

Training goal	*Rest interval length*
Hypertrophy	1.5–3 minutes
Strength	2–5 minutes
Power	2–5 minutes

Additional literature examined the effect of cluster set configurations on higher repetition sets that focus on muscle hypertrophy. A series of studies reported that high repetition sets with inter-repetition rest resulted in greater gains in strength and power, while producing similar gains in lean body mass (Oliver et al., 2013), greater total volume load and power, similar anabolic hormonal response, and decreased metabolic stress (Oliver et al., 2015), and maintained force, velocity, and power (Oliver et al., 2016) compared to traditional sets. Additional research indicated that cluster sets that utilised 30 second rest intervals between either two or four repetitions within a set of 12 maintained force, velocity, and power (Tufano et al., 2016c), and allowed for greater force, total work, and time under tension (Tufano et al., 2016b). Considering the metabolic demand that high repetition sets place on the body (Gorostiaga et al., 2012, Gorostiaga et al.,

2010), which may limit the utilisation of specific loads as the number of sets increases (de Salles et al., 2009, Buresh et al., 2009), the benefits of using cluster sets should not be overlooked.

Practitioners must take note of the amount of total training time required if certain rest intervals are implemented within cluster set configurations. For example, previous research noted that performing six, two repetition clusters for a set of 12 total repetitions may take longer than performing three, four repetition clusters (Tufano et al., 2016c). Smaller clusters require a larger amount of training time due to the increased amount of rest taken within a set. Considering that some sport governing bodies set strict guidelines on the amount of time for team activities, it is important for practitioners interested in using cluster sets to choose cluster set configurations that are both time efficient and effective at managing fatigue. For a more thorough discussion on the theoretical and practical applications of cluster sets, readers are directed to a recent review (Tufano et al., 2016a). Cluster set rest interval recommendations are summarised in Table 14.2.

Potentiation complex rest intervals

While the previously discussed rest intervals may be specific to traditional resistance training exercises, unique rest intervals may exist when implementing potentiation complexes. There are a number of factors that may affect the magnitude of potentiation expressed (Suchomel et al., 2016a, Tillin and Bishop, 2009). However, a portion of the existing potentiation literature has focused on examining the effect that various rest intervals have on the magnitude of potentiation expressed. Following a potentiating stimulus, both a state of fatigue and potentiation exist (Fowles and Green, 2003, Rassier and Macintosh, 2000, Hodgson et al., 2005, Sale, 2002). The interplay between fatigue and potentiation may be acutely modeled on the fitness-fatigue paradigm (Zatsiorsky, 1995), where the subsequent performance is the result of the interaction between fatigue and the fitness after-effects that are the result of an exercise stimulus. While meta-analyses indicated that rest intervals ranging three to seven minutes, seven to ten minutes (Wilson et al., 2013), and eight to twelve minutes (Gouvêa et al., 2013) produced positive moderate practical effects, additional literature indicated that the type, intensity, and duration of the exercise may determine whether fatigue or potentiation is dominant over the other

(Masiulis et al., 2007). Thus, it should come as no surprise that certain protocols may produce positive moderate practical effects as early as two minutes post-stimulus (Suchomel et al., 2016c) or as late as 15 or 20 minutes post-stimulus (Gilbert and Lees, 2005). Therefore, practitioners should consider that each individual potentiation complex possesses unique characteristics and may therefore have its own ‘optimal’ rest interval.

TABLE 14.2 Cluster set rest interval length to achieve specific training goals. Adapted from Haff (2016)

Training goal	*Cluster set rest interval length*
Hypertrophy	5–15 seconds
Strength	20–25 seconds
Power	30–40 seconds

Another factor that may affect the rest interval during various potentiation complexes is the relative strength of the individuals completing the protocol. Previous literature has indicated that strong relationships exist between an individual’s relative strength and the magnitude of potentiation expressed (Suchomel et al., 2016d, Seitz et al., 2014, Suchomel et al., 2016b). This idea is supported by the notion that stronger individuals may be able to tolerate a more fatiguing protocol given their frequent exposure to high intensity loading during training (Stone et al., 2008). Moreover, additional literature noted that stronger individuals potentiate earlier (Suchomel et al., 2016d, Seitz et al., 2014, Jo et al., 2010) and to a greater extent compared to weaker individuals. Thus, when designing potentiation complexes for athletes, practitioners should ensure that they take the athlete’s relative strength into account.

SECTION 2 – PRACTICAL APPLICATIONS

MODIFICATIONS FOR APPROPRIATE EXERCISE PERFORMANCE

Appropriate modifications/alternatives may need to be made in order for an athlete to safely perform a specific exercise or receive a given training stimulus. Whether it may be inexperience with an exercise or a lack of quality coaching, some athletes have difficulty performing certain exercises. Thus, it is important to provide athletes with consistent coaching modifications to help them learn and/or improve their technique in order to perform exercises correctly.

Previous recommendations were made to maximise leg muscle activation and minimise the risk of injury during the back squat (Comfort and Kasim, 2007). Briefly, an athlete's feet should be wider than shoulder-width apart with a natural foot position (McCaw and Melrose, 1999, Ninos et al., 1997), unrestricted movement of the knees while the heels maintain contact with the floor (Fry et al., 2003), a forward or upward gaze (Donnelly et al., 2006), and full ROM (115–125° of knee flexion) (Caterisano et al., 2002, Ninos et al., 1997) as long as the athlete is able to maintain a lordotic curve or neutral spine. Some athletes may have difficulty reaching the desired squat depth due to several potential issues (e.g., inexperience, stance, lack of flexibility, balance, etc.). Some common methods to implement that may help an athlete achieve the desired squat depth may be to modify their stance width and/or rotating their toes out (i.e., hip external rotation). These modifications will open up the hip joints and allow for greater displacement of the athlete's body. While the above provides one example, additional technique recommendations have been made for the bench press (Green and Comfort, 2007) and pull-up/lat pull-down (Leslie and Comfort, 2013) exercises.

Footwear

While some athletes may be able to effectively squat to the desired depth by adjusting their stance width or turning their toes out, a pre-existing anatomical limitation or lack of flexibility within the ankle may still prevent

an athlete from performing a good squat. An additional consideration may be to slightly elevate the heels of athletes in order to lessen the effect that this limitation has on their squat performance. This may be accomplished by placing small weights under an athlete's heels or by purchasing weightlifting shoes. Previous literature has indicated that weightlifting shoes may allow for a greater squat depth, an upright torso, and greater stability to be achieved (Legg et al., 2017, Hughes and Prescott, 2015). Further work has suggested that weightlifting shoes may reduce the forward trunk lean of individuals, reducing potential shear stress in the spine, and also increase knee extensor muscle activation compared to running shoes (Sato et al., 2012). While the addition of weightlifting shoes will not inherently fix poor squat technique by themselves, it appears that they may allow athletes to achieve a greater squat depth, allow for a more vertical torso, improve stability, and increase muscle activation, which may lead to improvements in strength and potential reductions in injuries.

Weightlifting movements

The weightlifting movements (i.e., snatch and clean and jerk) and their derivatives are popular exercises within resistance training programs. However, they are often described as technically complex movements that are difficult to teach and for athletes to learn. Practitioners may find that some of their athletes may have difficulty learning a particular aspect of a full weightlifting movement (e.g., performing the first pull to the knee, transitioning to the second pull starting position, properly executing the catch phase, etc.). While this may deter some practitioners from prescribing weightlifting movements within their athletes' training programs, it should be noted that a number of derivatives exist that serve as effective substitutes (Suchomel et al., 2017). Scenarios that a practitioner may face when it comes to choosing an alternative weightlifting movement are displayed in Figures 14.1 and 14.2.

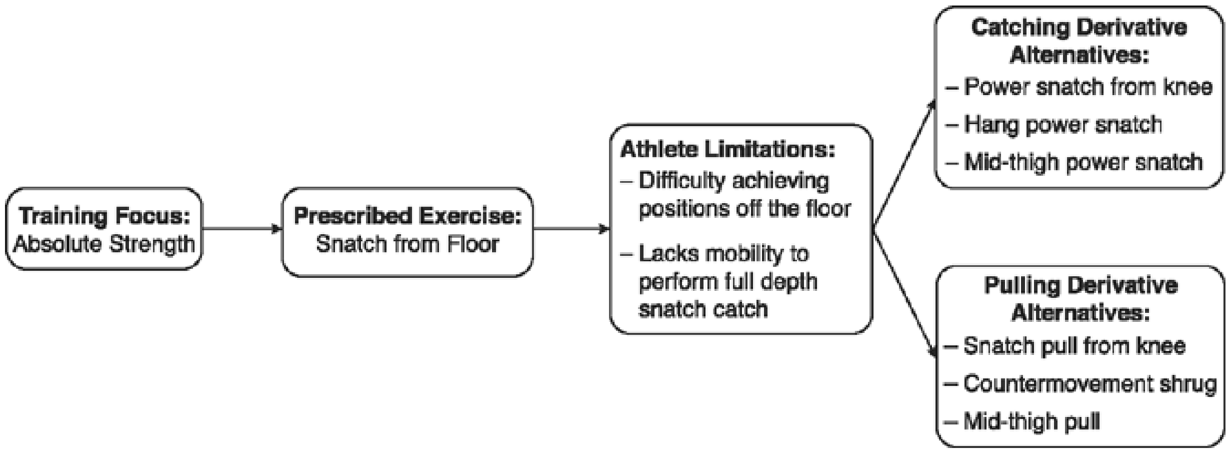

FIGURE 14.1 Scenario requiring weightlifting alternatives for the snatch.

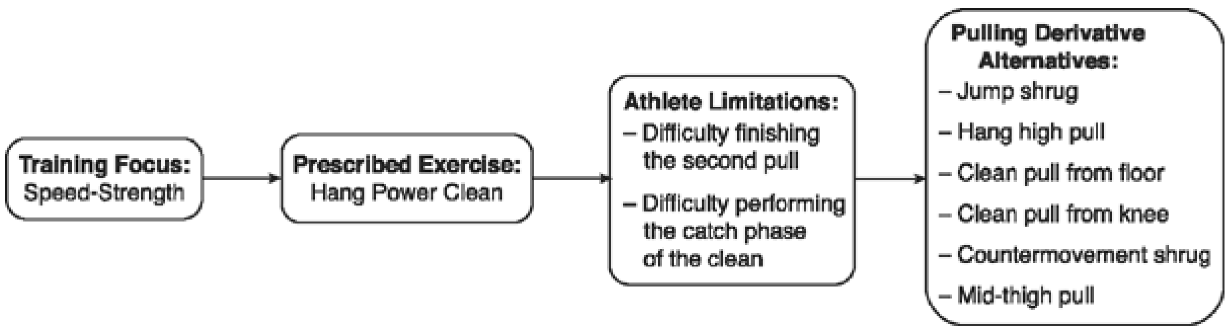

FIGURE 14.2 Scenario requiring weightlifting alternatives for the hang power clean.

Unilateral training alternatives

Although the back squat exercise is a popular choice for lower extremity strength development, it is not without its limitations. As mentioned above, it is possible that the back squat may result in a greater forward lean compared to the front squat. Moreover, this may result in greater shear forces in the spine experienced by athletes. While proper technique modifications with the potential assistance of weightlifting shoes may mediate these issues, practitioners should also note that unilateral exercises, such as the rear foot elevated split squat, may serve as effective exercise alternatives. Previous literature indicated that unilateral training resulted in similar improvements in strength and power adaptations (McCurdy et al., 2005), as well as sprint speed and agility (Speirs et al., 2016). Further research indicated that a modified split squat resulted in greater gluteus medius, hamstring, and quadriceps activation compared to a bilateral squat

(McCurdy et al., 2010). These authors also noted that the modified split squat also maintained a more upright torso, which may potentially decrease shear force stress in an athlete’s lower back. This notion is supported by large effect size differences in left and right erector spinae activation between the rear foot elevated split squat and back squat exercise (Bellon et al., 2013). Collectively, the previous literature that has compared the effects of unilateral and bilateral lower extremity exercises indicates that unilateral exercises may be suitable alternatives for practitioners to prescribe, especially if an athlete is hampered by lower back pain. However, it should be noted that unilateral exercises may be best implemented as assistance exercises to bilateral lifts due to the decreased stability of a single limb being used.

CUEING AND FEEDBACK

Sport and strength and conditioning coaches traditionally have their own methods of cueing and providing feedback to athletes. While this is done to get athletes to perform an exercise or task in a certain manner, practitioners should note that how they provide cues and feedback may have a profound effect on the training stimulus that athletes receive.

Cueing

Previous work by Wulf (2007) indicates that cues and feedback that are external (i.e., athlete focuses on movement effect) are much more effective than those that are internal (i.e., athlete focuses on his or her body movements) when it comes to how motor skills are performed, learned, and retained. A recent review that discussed instructions and cues for improving sprint performance echoed these sentiments, suggesting that cueing should provide an external focus for the athlete (Benz et al., 2016). The authors suggested that coaches should consider providing external and/or neutral cues at a 100% frequency while keeping the quantity of instructions low. A similar strategy may be applied when cueing athletes in the weight room. For example, if an athlete is performing an overhead press and the training emphasis is speed-strength, an appropriate external cue may be: ‘Make the bar rattle at the top.’ Compared to an internal cue of: ‘Contract your arms

faster to push the weight.' From the athlete's perspective, the external cue gives them the goal based on a sound that would indicate that they moved the weight quickly. As athletes become more experienced, smaller cueing phrases may be used. At this point, an athlete and their coach understand what a specific cue means for them compared to another athlete. A common cue used in the weight room that can be applied to many scenarios is: 'Stay tight!' As previously mentioned, this cue may be sufficient for a more experienced athlete; however, it may also mean something different to two different athletes. It is recommended that practitioners apply an external focus strategy when it comes to cueing exercises, keeping in mind that the amount of information provided should be concise and specific to each athlete.

Feedback

Similar to coaching cues, research supports the use of providing external feedback to athletes as opposed to internal feedback. Coaches can provide feedback in a variety of ways including audio (e.g., verbal discussions), visual (e.g., video analysis and/or demonstrations), and quantitative (e.g., data display). Previous research demonstrated that augmented feedback (including coaching and 2-D video analysis) resulted in greater kinetic and kinematic adaptations during the power snatch exercise compared to a control group (Winchester et al., 2009). While this method was effective, another study examined the use of the method of amplification of error (MAE) and how it affected snatch performance compared to traditional coaching feedback (Milanese et al., 2017). Briefly, MAE allows athletes to learn to correct their movements by understanding how to perform the movement incorrectly. The authors indicated that the MAE group produced greater kinematic improvements of snatch technique compared to direct instruction only. Finally, a practical example of quantitative feedback may be through the use of velocity-based training (Mann et al., 2015). In order to achieve a specific velocity during training, the athlete may need to be provided with immediate velocity feedback. Using current technologies, an athlete may see the velocity they produced and adjust the weight accordingly in order to meet the goal of that particular training session.

The amount of feedback given to an athlete may be based on their training age. However, practitioners should be cautious as to how much

feedback is provided at any given time. Athletes may not be able to receive multiple pieces of information and perform an exercise effectively, especially if feedback is provided after every repetition. In order to effectively provide feedback to an athlete, practitioners should choose one point of emphasis that an athlete can work on during subsequent training sets. Practitioners should focus on the most important aspect that is hindering appropriate exercise performance before fine-tuning technique with smaller corrections. This is especially true if an athlete is putting themselves at risk for injury.

RANGE OF MOTION SPECIFICITY EXAMPLE

While practitioners may have their opinions on what ROM should be performed (full or partial), the decision to increase or decrease the ROM may be justified if the athlete is returning from injury or training within specific training periods where larger or smaller volume-loads may be needed to elicit specific training adaptations. The most obvious instance would include an athlete's return from an injury. In this situation, practitioners may not be as focused on improvements that will transfer to the athlete's sport/event, but instead may be focused on having the athlete regain the competency of an exercise using a reduced ROM. Some of this training may be dictated by the sports medicine staff; however, strength and conditioning practitioners should be aware and involved in some capacity as well. Ultimately, once an athlete again achieves the desired ROM during a given exercise, strength and conditioning practitioners may take over and transition the athlete into a return to fitness phase.

While the above scenario certainly occurs, it should be noted that it may be practical to reduce the ROM of a given exercise during certain times of the training year in order to maintain certain abilities or reach peak adaptations. For example, it may be preferable during certain times of year to perform half-squats or quarter-squats in order to dissipate any accumulated fatigue and to peak for a certain event. If a practitioner is working with a sprinter, reducing the ROM of the work sets may be advantageous from multiple aspects. For example, it may be practical to progress a sprinter from performing full squats and adding in half-squats and quarter-squats during certain phases of training (Bazyler et al., 2014). Using a progression may not only reduce an athlete's neuromuscular fatigue

due to less eccentric work performed, but partial squats may also increase the mechanical specificity of their training for maximum velocity. This notion is supported by recent research that indicated that training with quarter-squats resulted in greater improvements in 40-yard sprint time and vertical jump height compared to training with full and half-squats (Rhea et al., 2016). However, it should be noted that additional literature has suggested that the complete removal of full ROM squats in trained individuals may result in a plateau and possible reductions in 1RM strength (Harris et al., 2000, Painter et al., 2012). Thus, practitioners should consider prescribing a combination of both full and partial ROM squats in order to improve/maintain overall and angle-specific strength.

SUMMARY

While there are a number of factors that a practitioner must consider when prescribing resistance training exercises to their athletes, each individual factor should not be overlooked. Exercise technique considerations such as the ROM performed and the grip/stance used may alter the training stimulus for athletes. In addition, practitioners must consider mechanical demands of each exercise including their force-velocity characteristics, the inclusion/exclusion of the SSC, load placement, direction in which the force is produced, and ballistic/non-ballistic nature. Finally, the rest intervals used, whether they are inter-set, intra-set, or within potentiation complexes, should be specific to the characteristics that are being developed within each phase of training.

From a practical standpoint, practitioners should implement appropriate modifications to exercises in order to provide an effective training stimulus for their athletes. In addition, consistent external coaching cues combined with specific feedback will improve the learning and retention of challenging tasks. Finally, practitioners should note that a decreased ROM combined with a sufficient load may provide an effective training stimulus that is more specific to positions achieved during different phases of sport training.

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CHAPTER 15

Weightlifting for sports performance

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INTRODUCTION

This chapter should provide the reader with information regarding the existing literature on weightlifting movements and the theoretical rationale as to why they are used in athletes' training programs (Section 1). Section 2 will then provide practical examples to allow the reader to implement weightlifting movements and their derivatives using an evidence-based approach.

The term 'weightlifting' refers to the sport in which competitors perform the snatch and the clean and jerk, attempting to lift the maximum amount of weight. Weightlifting in this sense is different from the general term 'resistance training', which refers to all other forms of training in which an individual is moving against a resistive load. However, the weightlifting movements (i.e., snatch, clean, and jerk) and their derivatives may also be used within resistance training programs in order to train the strength and power characteristics of athletes who are not competing in the sport of weightlifting.

SECTION 1

THE EFFECTIVENESS OF WEIGHTLIFTING MOVEMENTS

While both weightlifting and other forms of resistance training may improve an athlete's lower body strength and power, research suggests that weightlifting movements and their derivatives may provide superior training effects compared to other methods (Hoffman et al., 2004; Tricoli et al., 2005; Otto III et al., 2012; Teo et al., 2016; Arabatzi and Kellis, 2012; Chaouachi et al., 2014; Channell and Barfield, 2008). These findings are attributed to two primary reasons, movement specificity and the overload that the athlete can be subjected to.

Movement specificity

The most common movement in sports is the coordinated extension of the hip, knee, and ankle joints (plantar flexion), termed 'triple extension'. Jumping, sprinting, and change of direction tasks require the completion of the triple extension movement. A similar coordinated triple extension movement takes place during the second pull phase of weightlifting movements (see 'Weightlifting Technique'), which allows these movements to transfer to sports performance. Due to the similarities between the triple extension of sports movements and the second pull of weightlifting movements, it should come as no surprise that better performance of weightlifting movements is related to better performance during sprinting and jumping (Carlock et al., 2004; Hori et al., 2008).

Overload

Weightlifting exercises are coordinated movements in which an athlete moves a moderate-heavy load with ballistic intent. While other resistance training methods may be used to train lower body strength and power (e.g., free weights, plyometrics, kettlebells, etc.), these methods are typically not performed in the same manner as weightlifting movements. For example, training with the back squat may produce high forces but with less velocity,

whereas plyometric exercise may produce high velocities but with less force. This is supported by previous literature that has demonstrated that the power outputs of the snatch, and clean and jerk were superior to core exercises such as the squat and deadlift (Garhammer, 1980; Garhammer, 1991). Additional literature indicated that standard resistance training exercises resulted in reduced force production (i.e., deceleration) during as much as 45% of the range of motion (Newton et al., 1996).

WEIGHTLIFTING TECHNIQUE

During the snatch in a weightlifting competition, the lifter must lift the barbell from the floor to an overhead position, receiving the weight with the arms fully extended, in one continuous motion (Figures 15.2–15.7). The clean is characterised by lifting the barbell from the floor to a resting position across the front of the lifter's shoulders (Figures 15.2–15.7). As a continuation of the clean, the jerk is completed by lifting the barbell from the shoulders to an overhead position, receiving the weight with the arms fully extended (Figures 15.8–15.13). The technique of each lift is described below.

Snatch/clean first pull

The first pull refers to the initial movement of the barbell from the floor to a position just above the knee. The starting position of each athlete will be based on their anthropometric characteristics such as their height, body mass, and somatotype as well as their range of motion and flexibility. Athletes should position themselves so that they are centered on the bar with their feet flat and positioned about hip-width apart and the barbell positioned over the middle of their feet. The recommended grip to use with weightlifting movements is the hook grip (Figure 15.1). Whether performing a clean or snatch variation, the hands may be positioned more closely together or farther apart, respectively. The elbows should be pointed outward to prevent excess elbow flexion that may hinder the transfer of force to the barbell. The barbell should almost be in contact with the athlete's lower leg, their knees should be in line with their feet, and their hips should be slightly higher than their knees. The position of the upper

body should include extended arms, shoulders in front of the bar, an elevated chest, shoulder blades pulled back, and a slightly arched (natural curve) or flat back. Finally, the athlete's head should be neutral with their eyes looking forward (Figure 15.2).

FIGURE 15.1 Hook grip – thumb wraps under the bar with the fingers wrapped around the thumb and bar.

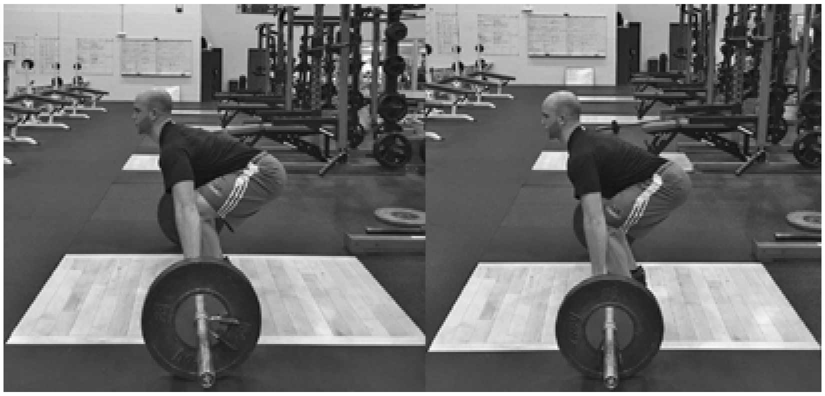

FIGURE 15.2 Starting position for the snatch (left) and clean (right).

FIGURE 15.3 The end of the first pull for the snatch (left) and clean (right).

After reaching the correct starting position, athletes should inhale to increase their intra-abdominal pressure and remove any slack that may still exist within their arms. The athlete should then begin the lift by pushing into the ground through the centre of their feet while elevating their hips and shoulders at the same rate and maintaining the angle of their back, shoulders over the barbell, and fully extended arms. While elevating the barbell, the knees move backward while the lower legs reach a near vertical position, resulting in a shift of the centre of pressure from the mid-foot to the heels (Figure 15.3).

Snatch/clean transition

The transition phase refers to the movement of the barbell from a position just above the knee to the mid-thigh ‘power’ position in preparation for the second pull. An effective transition phase requires the athlete to re-bend their knees to a position in front of the barbell as it moves from the knee to the mid-thigh shifting the centre of pressure from the heels to the mid-foot. The athlete’s hips should move over their ankles, resulting in a vertical torso, extended arms, and knees bent to approximately 125–135° (Figure 15.4).

FIGURE 15.4 Mid-thigh (power) position side view for the snatch (left) and oblique view for the clean (right).

Snatch/clean second pull

Upon reaching the mid-thigh position, athletes perform the second pull movement by pushing into the ground and rapidly extending their hips, knees, and ankles (plantar flexion) and shrugging their shoulders (Figure 15.5). This movement causes the barbell to rise vertically and results in the greatest force, rate of force development (RFD), velocity, and power (Enoka, 1979; Garhammer, 1980; Garhammer, 1982). Athletes should keep their arms extended for as long as possible during the second pull to ensure maximum force transfer to the barbell. However, the athlete’s arms will bend due to the upward momentum of the barbell and the failure to elevate

the torso any higher. It should be noted that while the second pull results in the completion of certain weightlifting derivatives (see Weightlifting Pulling Derivatives below), others require the athlete to catch or receive the weight.

Snatch/clean catch

Following the second pull, a snatch variation requires the athlete to rotate their hands and elbows around the barbell, moving from a vertical position above the barbell into a position below the barbell. Simultaneously, the athlete will flex their hips, knees, and ankles (dorsiflexion), drop and pull themselves into an overhead squat position while their feet may move slightly outward to a more stable position. The athlete should receive the barbell in an overhead squat position with their elbows locked out at the same time as their feet land flat on the ground in the desired squat depth while maintaining an upright torso and normal lumbar curve (Figure 15.6). Figure 15.7 displays a power snatch catch variation.

FIGURE 15.5 Second pull of the snatch (left) and clean (right).

A clean variation requires the athlete to rotate their elbows around the barbell from a position above the barbell into a horizontal position in front of the barbell. The athlete will flex their hips, knees, and ankles (dorsiflexion), drop and pull themselves into a front squat position while

their feet may move slightly outward to a more stable position. The athlete should receive the barbell in a front squat position on the front of their shoulders with their elbows pointed forward, their upper arm nearly parallel with the ground, and a relaxed grip at the same time their feet land flat on the ground in the desired squat depth while maintaining an upright torso and normal lumbar curve (Figure 15.6). Figure 15.7 displays a power clean catch variation.

FIGURE 15.6 Catch position of the snatch (left) and clean (right).

FIGURE 15.7 Power snatch (left) and power clean (right) catch positions.

Snatch/clean recovery

After becoming stable in the desired squat depth for snatch and clean variations, the recovery phase requires the athlete to return to a standing position maintaining the overhead or front squat position (Figure 15.8). The athlete should maintain an upright torso while extending their hips and knees to return to a standing position.

Jerk starting position

As a continuation of the clean exercise, or from a rack or training blocks, the athlete should start in standing position with their feet approximately shoulder-width apart, an upright torso, and the barbell racked across the front of their shoulders with their upper arms nearly parallel to the floor. The athlete's eyes should be forward and their chin tucked (Figure 15.9). An alternative variation would allow the athletes to start with the barbell resting on their upper back, similar to a back squat.

Jerk dip

Before the athlete begins the lift, the athlete should take a deep breath in order to elevate the rib cage, brace the other trunk musculature, and create intra-abdominal pressure. Following the breath, the athlete will simultaneously flex their hip and knee joints and descend to a quarter-squat position where the knees are flexed to approximately 125–135° (Figure 15.10). As the athlete descends, they should keep their elbows elevated so as to not let the barbell move away from their centre of mass. This common error may result in the athlete pushing the barbell more forward rather than vertically during the drive phase. The dip phase should be completed fairly rapidly without pausing in the bottom position in order to receive the greatest stretch-shortening cycle benefits (i.e., greater use of stored elastic energy and less force dissipation).

FIGURE 15.8 Recovery position for the snatch (left) and clean (right).

FIGURE 15.9 Starting position for a jerk variation.

FIGURE 15.10 Completion of the dip phase of the jerk.

FIGURE 15.11 The drive phase of the jerk.

FIGURE 15.12 Split jerk receiving position.

Jerk drive

Upon reaching the bottom of the dip phase, the athlete should immediately, without pausing, rapidly extend their hip, knee, and ankle joints in order to drive the barbell up vertically (Figure 15.11). The triple extension movement should cause the barbell to elevate off the athlete’s shoulders and pass in front of their face. It is important to remind the athlete to tuck their chin during the drive phase in order to prevent possible injury. As the barbell continues to elevate, the athlete should grasp it with an overhand

grip. Simultaneously, the athlete's feet are either beginning to split forward and backward (split jerk) or laterally (power jerk). The athlete's torso should remain upright and rigid in preparation to receive the load overhead.

Jerk receiving positions

Depending on the variation used, split jerk or power jerk, the athlete's feet will continue to split forward and backward or laterally. Coaches should note that the splitting of the feet should not be a jumping motion, but rather a continuation of the drive phase. During the split jerk (Figure 15.12), the athlete should 'jab' the front foot forward so that it is flat on the ground with the pressure on the heel. The athlete's front knee should flex and remain in line with their toes. Simultaneously, the athlete's back foot moves backward and is planted on the ball of their foot with their heel off the ground. The back leg should be slightly bent to allow for the absorption of force as the load is received overhead. As the athlete splits their legs, they should also continue the drive phase by pushing the barbell vertically and receiving it overhead with their elbows in a locked position. The barbell should be received with a braced torso in a position where the barbell is directly above the back of the head (Figure 15.12).

FIGURE 15.13 Power jerk receiving position.

FIGURE 15.14 Jerk recovery.

A power jerk variation follows a similar sequence of movements through the drive phase. Instead of splitting the feet forward and backward, the athlete moves their feet slightly laterally and flexes their hips and knees into a quarter-squat position. At this point, the athlete continues to drive the barbell upward before receiving in the previously described overhead position (Figure 15.13).

Jerk recovery

In order to recover from a split jerk position, the athlete should first step backwards with their front foot until it is close to the body and then step forward with the back foot until the legs are together all while maintaining an upright posture and the barbell held overhead with locked arms (Figure 15.14). The movements of the legs should be completed in this order to allow for the centre of mass to be moved backwards against a braced back leg rather than creating forward momentum by moving towards the front leg.

Once in a stable receiving position during the power jerk, the athlete should extend their hips and knees while maintaining an upright torso and holding the barbell overhead with locked arms to return to a standing position (Figure 15.14).

WEIGHTLIFTING DERIVATIVES

As mentioned above, the primary weightlifting movements are the snatch, clean, and jerk. However, it should be noted that there are a number of partial lifts (i.e., weightlifting derivatives) that exclude part of the full snatch, clean, or jerk movements. Despite removing an aspect of the lift, weightlifting derivatives may also be effectively implemented into resistance training programs for athletes. It should be noted that weightlifting derivatives may be further sub-divided into weightlifting catching and pulling derivatives.

Weightlifting catching derivatives

Practitioners often refer to weightlifting derivatives that include catching the load overhead as described during a snatch derivative or across the shoulders as performed during a clean derivative. In addition to producing high power outputs during the triple extension movement, it is generally believed that the catch phase will train an athlete to decelerate an external load. The ability to decelerate a load is an important characteristic for athletes in sports such as rugby, American football, and wrestling, and thus, the benefits of a proper catch phase should not be discounted. Previous research has indicated that weightlifting catching derivatives may be used as a training tool to improve landing characteristics (Moolyk et al., 2013).

As with any exercise, the athlete’s technique is vital to receive the optimal training stimulus and prevent injury. This is especially true when it comes to weightlifting movements and their derivatives as they are highly complex with regard to technique. A number of studies have examined factors that may influence the proper completion of the snatch and clean and jerk exercises. Researchers have examined the effect that loading has on snatch and clean and jerk technique (Häkkinen et al., 1984), snatch technique of weightlifters at different levels (Harbili and Alptekin, 2014; Schilling et al., 2002; Kauhanen et al., 1984), technique changes following feedback (Winchester et al., 2009), and the technique differences between successful and unsuccessful snatch attempts (Gourgoulis et al., 2009; Stone et al., 1998). These findings are beneficial in that they may help improve coaching cues and the focus on critical aspects of each lift.

The most common snatch and clean derivatives prescribed are the power clean/snatch and hang power clean/snatch. Thus, in an attempt to aid practitioners and their programming decisions, researchers have examined

these exercises by attempting to find the load that produces the greatest magnitude of power (i.e., the optimal load). This research has indicated that loads ranging from 70–80% one repetition maximum (1RM) may provide the optimal training load for the power clean (Comfort et al., 2012a) and hang power clean (Kilduff et al., 2007; Kawamori et al., 2005). Interestingly, a paucity of research has examined the optimal training load for snatch catching derivatives. However, the information presented within the literature surrounding the optimal training loads of weightlifting catching derivatives is important for practitioners when it comes to prescribing loads during various training phases. However, practitioners should consider the sport/event of their athlete(s) as the optimal load may be specific to the system (athlete and load), barbell, or joint (McBride et al., 2011). Thus, practitioners should determine which magnitude of power is specific to the athlete's sport/event. For example, power applied to the barbell is essential for weightlifters, whereas power applied to the system is arguably more important in terms of assessing the development of lower body power. A recent review discussed optimal loading ranges for lower body exercises and concluded that a range of loads should be prescribed when training for maximal power output (Soriano et al., 2015). Additional literature supports this notion (Haff and Nimphius, 2012).

A third aspect of the extant literature focuses on different cluster set configurations when it comes to implementing weightlifting catching derivatives. The results of these studies indicate that the use of cluster sets offset the increase in perceived effort (Hardee et al., 2012a), allowed for technique to be maintained (Hardee et al., 2013), and also allowed power output to be maintained throughout the set (Hardee et al., 2012b). From a practical standpoint, it appears that 20–40 seconds of inter-repetition rest may allow the athlete to experience a better training stimulus when training with the clean derivatives.

Weightlifting pulling derivatives

Weightlifting pulling derivatives, as the name suggests, are weightlifting derivatives that remove the catch phase and finish with the completion of the second pull (Figure 15.5). Examples of weightlifting pulling derivatives discussed within the literature include the clean/snatch mid-thigh pull, pull from the knee, pull from the floor, countermovement shrug, hang high pull,

and jump shrug (Suchomel et al., 2017a). Some of the benefits of the above derivatives include decreased exercise complexity regarding technique, a potential decreased learning and teaching time for the movements, a potential reduced impact on specific joints, and a greater ability to overload the triple extension movement (Suchomel et al., 2015b). Due to the number of benefits that may enhance the abilities of athletes, research has examined weightlifting pulling derivatives in several capacities including comparisons with weightlifting catching derivatives, loading effects, and different set configurations.

Results of previous research have indicated that weightlifting pulling derivatives may produce a comparable (Comfort et al., 2011b, 2011a) or superior (Suchomel and Sole, 2017; Suchomel et al., 2014b; Kipp et al., 2016) training stimulus compared to weightlifting catching derivatives with regard to peak force, velocity, power, RFD, and impulse. Further research indicated that the load absorption demands (work, mean force, duration) of weightlifting pulling derivatives are similar or greater compared to weightlifting catching derivatives (Suchomel et al., 2017b; Comfort et al., 2016). It should be noted that the previous studies are cross-sectional studies, and thus, further research is warranted to determine if longitudinal training with catching or pulling derivatives would produce different results. However, it is clear that practitioners must consider the potential benefits of using weightlifting pulling derivatives when it comes to enhancing the force production characteristics of their athletes.

Similar to weightlifting catching derivatives, much of the research that focuses on weightlifting pulling derivatives has examined the effect that the external load has on various kinetic and kinematic variables. Through examining different loads, sport scientists and practitioners can determine which loads provide the optimal training stimulus for athletes within the context of each exercise. Furthermore, these findings may then be applied within resistance training programs. For example, the goals of maximal strength and absolute strength training blocks are to enhance the maximal force production capacity of the athlete and to begin the initial stages of enhancing their RFD characteristics against heavy external loads. Thus, weightlifting pulling derivatives that allow for the use of heavier training loads may aid in the development of the desired characteristics. Previous research has demonstrated that the mid-thigh pull (Comfort et al., 2015; Comfort et al., 2012b) and pull from the floor (Haff et al., 2003) may use

loads in excess of an athlete’s 1RM power clean because these derivatives do not require athletes to drop under the barbell and catch the load. Specifically, practitioners may prescribe loads up to approximately 120–140% of their 1RM power clean, as long as proper technique is maintained. Based on these findings, it is clear that weightlifting pulling derivatives may enhance an athlete’s force production characteristics. In fact, implementing the mid-thigh pull and pull from the floor may result in force production gains that may not occur if the practitioner only implements weightlifting catching derivatives as the latter exercises cannot exceed loads beyond their 1RM.

Another example would be selecting exercises that maximise power production during speed-strength training blocks. While high force production is emphasised during maximal strength and absolute strength training blocks, the goals of a speed-strength training block are to peak the RFD and power characteristics of athletes prior to competition. Thus, weightlifting pulling derivatives that are the most ballistic in nature may be useful exercises that may aid in the development of these characteristics. Previous research has examined the effect that load has on the jump shrug (Suchomel et al., 2013) and hang high pull (Suchomel et al., 2015a). The results of these loading studies indicated that the lightest loads examined (i.e., 30 and 45% of 1RM hang power clean) produced the greatest magnitudes of velocity and power. In contrast to exercises such as the mid-thigh pull and pull from the floor, it is clear that the jump shrug and hang high pull may fall on the opposite end of the loading spectrum, but may still be useful during certain phases of training (Suchomel et al., 2017a).

A third area that is lacking in depth for weightlifting pulling derivatives is research that examines different set configurations. For example, the aforementioned studies may provide the practitioner with the choice of exercise and the potential loads that coincide as an effective training stimulus, however, only one study to date has examined different set configurations (traditional, undulating, and cluster) when performing a weightlifting pulling derivative (Haff et al., 2003). The results of this study indicated that the use of a cluster set may result in greater barbell velocity and displacement during the clean pull from the floor compared to a traditional set. From a practical standpoint, this type of information is crucial as it may alter the training stimulus an athlete experiences, namely

the quality of work. However, further research is needed in this area before concrete conclusions can be drawn.

SECTION 2 – PRACTICAL APPLICATIONS

DEVELOPING AN ATHLETE'S FORCE-VELOCITY PROFILE

As described in Chapter 2, one of the primary goals of a strength and conditioning practitioner is to develop the force-velocity profile of their athletes in order to enhance important force production characteristics such as impulse, RFD, and power. Haff and Nimphius (2012) indicated that the most effective way to develop an athlete's force-velocity profile is through the use of training methods that will develop both the force and velocity ends of the spectrum. While this process can be completed using different set and repetition schemes, warm-up and warm-down sets, and various intensities during core exercises (squat, bench press, etc.), a sequenced progression of weightlifting derivatives may also develop the entire force-velocity profile of an athlete (Suchomel et al., 2017a). Figure 15.15 displays the theoretical force-velocity relationship specific to weightlifting derivatives.

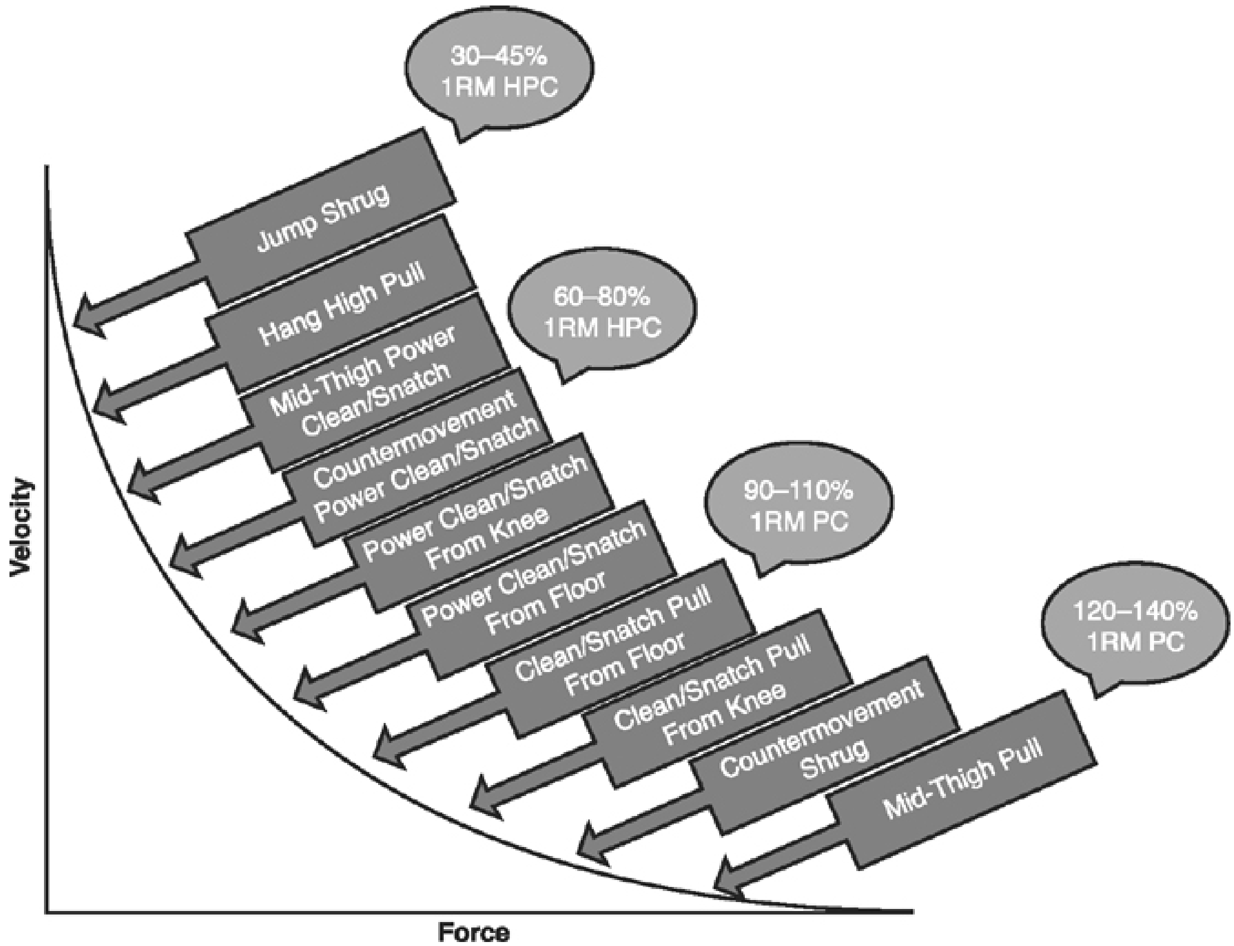

FIGURE 15.15 Theoretical force-velocity (power) curve with respect to weightlifting derivatives; modified from Suchomel et al. (2017a). 1RM = one repetition maximum, HPC = hang power clean, PC = power clean.

The previously discussed literature supports the notion that weightlifting derivatives such as the mid-thigh pull, countermovement shrug, pull from the knee, and pull from the floor may all be used to develop high force production characteristics due to the decreased displacement of the load during each movement. On the opposite end of the force-velocity curve are weightlifting derivatives that are characterised by higher velocities. The jump shrug, hang high pull, mid-thigh clean/snatch, and countermovement (hang) clean/snatch are weightlifting derivatives that are highly ballistic and are typically programmed with low-moderate loads. While the placement of derivatives within Figure 15.15 is supported by evidence, it should be noted that the load prescribed may influence the position of each exercise on the force-velocity curve. For example, while the mid-thigh pull enables athletes to use the heaviest loads (i.e., 140% of 1RM power clean), power

production and velocity were maximised with the lightest load (i.e., 40% of 1RM power clean) (Comfort et al., 2015, Comfort et al., 2012b). (Please see Table 15.1 on pp. 267–269.)

As discussed in Chapter 8, previous literature suggests that a sequenced progression of training phases promotes the optimal development of an athlete's force-velocity profile (Minetti, 2002; Zamparo et al., 2002; Stone et al., 1982). Briefly, increases in work capacity and muscle cross-sectional area produced during a strength-endurance (hypertrophy) phase enhance an athlete's ability to increase their muscular strength. From here, increases in muscular strength will then enhance an athlete's potential to improve their RFD and power characteristics. A similar approach can be taken when prescribing weightlifting derivatives because certain lifts place greater emphasis on either force or velocity. Thus, specific weightlifting catching and pulling derivatives may be prescribed during resistance training phases in order to meet the goals of each phase and develop the force-velocity profile of the athlete. The following will discuss the implementation of weightlifting derivatives into various resistance training phases to promote the optimal development of an athlete's force-velocity profile.

Strength-endurance

The strength-endurance phase is characterised by a high volume of repetitions (usually 8–12) in exercises that use moderately heavy loads (60–70% 1RM). The purpose of this phase is to increase the athlete's work capacity, stimulate increases in muscle cross-sectional area, and refine exercise technique for subsequent training phases. Regarding the use of weightlifting derivatives within this phase, it is suggested that practitioners implement the clean/snatch pull from the floor, pull to the knee, and clean grip shoulder shrug for several reasons. First, the suggested derivatives serve as foundational exercises that enable the progression to more complex weightlifting movements. The inability to perform these exercises may lead to improper exercise technique of more complex derivatives, potentially impacting the training stimulus. Second, the clean/snatch pull from the floor enables athletes to overload the triple extension movement without experiencing the additional stress and complexity of performing the catch phase every repetition as fatigue develops. While the catch phase of certain weightlifting derivatives may enable the athlete to develop additional

performance characteristics as mentioned above, the high volume experienced during the strength-endurance phase may lead to a deterioration in form due to acute fatigue. Moreover, a decline in technique may alter catch phase mechanics and increase the likelihood of injury or compression stress. Finally, the suggested derivatives enable the development of important lower and upper body musculature that will be used to enhance the force-velocity profile during later training phases in tandem with exercises such as squatting, pressing, and pulling movements.

It should be noted that the athletic population may dictate which weightlifting movements are prescribed in a strength-endurance training block. For example, the clean/snatch pull from the floor may only be implemented with an athletic population whose technique is more stable and resilient to fatigue. Practitioners may also consider prescribing cluster sets of either two or five repetitions for the clean/snatch pull from the floor due to the high volume within the strength-endurance phase. As discussed in Chapter 14, the use of cluster sets may enable the athlete to maintain their technique, force production, and power output throughout each set leading to high quality work, enhanced work capacity, and force production adaptations with a high volume of repetitions. Moreover, the inter-repetition rest interval may allow the coach to provide additional feedback to the athlete.

Maximal strength

A maximal strength phase is used to increase an athlete's force production capacity using sets of four to six repetitions and moderately heavy to heavy loads (i.e., 80–90% 1RM, although potentially slightly higher with pulling derivatives). During this phase, practitioners should shift their focus to exercises that emphasise force production and enable the use of heavier loads. With this in mind, a limitation to weightlifting catching derivatives is that practitioners cannot prescribe loads greater than the athlete's 1RM. This however, is not the case for weightlifting pulling derivatives as exercises such as the clean/snatch pull from the floor, pull from the knee, and mid-thigh pull allow for loads greater than the athlete's 1RM to be used due to the elimination of the catch phase and decreased displacement of the load. The use of these exercises combined with heavier loads will

emphasise force production and train the high force portion of the force-velocity curve.

Absolute strength

Similar to the maximal strength phase, the goals of the absolute strength phase are to enhance the athlete's low repetition (two to three) force production (both magnitude and rate) characteristics using near maximal loads (90–95% 1RM or potentially as high as 120–140% 1RM with pulling derivatives). While the same exercises from the maximal strength phase may be prescribed to retain the athlete's capacity for high force production, additional derivatives that include a strength-speed component should be introduced to begin the enhancement of RFD. These exercises might include the hang power clean/snatch (Suchomel et al., 2014a), power clean/snatch, mid-thigh clean/snatch (Comfort et al., 2011b, 2011a), and the full clean and snatch. The combination of high force movements and introducing high velocity movements will ultimately contribute to the athlete's ability to further develop impulse, RFD, and power characteristics.

Strength-speed

The primary goals of the strength-speed phase are to further increase RFD and power, while also maintaining or potentially increasing the athlete's strength. Because previous literature has indicated that RFD and power are two of the most important characteristics regarding an athlete's performance (Stone et al., 2002; Morrissey et al., 1995), it is important to prepare the athlete to maximise these adaptations using the previously discussed training phases. Based on the phasic progression of resistance training phases, increases in muscular strength (Suchomel et al., 2016b) and RFD (Taber et al., 2016) from the previous training phases should, in theory, enhance the athlete's ability to augment their power characteristics.

Regarding the programming of weightlifting derivatives during the strength-speed phase, RFD and power characteristics may be enhanced using a combination of heavy and light loads. However, the emphasis within this phase is to move relatively heavy loads quickly in order to enhance RFD characteristics. Thus, the mid-thigh clean/snatch, countermovement clean/snatch, and power clean/snatch from the knee

(Suchomel et al., 2016a) may be used to develop the high velocity portion of the force-velocity curve, while the power clean, clean/snatch pulls from the floor, knee, and mid-thigh may develop the high force end of the force-velocity curve.

Speed-strength

The goals of the speed-strength phase are to produce peak adaptations in RFD and power prior to competition. In order to peak these abilities, a wide variety of weightlifting derivatives may be prescribed. Many of the previously described derivatives may be prescribed; however, the speed at which the movement is performed, and therefore the load, must be considered. For this reason, the jump shrug and hang high pull may be highlighted during the speed-strength phase due to their ballistic nature. A combined approach of prescribing heavy and light loaded derivatives should be implemented to optimise RFD and power adaptations. Thus, practitioners may prescribe a combination of the clean/snatch mid-thigh pull or pull from the floor and the jump shrug and hang high pull to focus on training each end of the force-velocity curve. Varying neurological demands will be placed on the athlete as the above combination will simulate overcoming the inertia of an external load from a static start (e.g., mid-thigh pull) and ustilise the stretch-shortening cycle (e.g., jump shrug), allowing them to optimise impulse, RFD, and power characteristics.

Another aspect to consider during the speed-strength phase is the load implemented with each exercise. Previous literature has suggested training at or near the loads that maximise power (Kawamori and Haff, 2004). As discussed above, loads of approximately 70–80% 1RM may provide the optimal training load for the power clean and hang power clean, while lighter loads (i.e., 30–45% 1RM of hang power clean) may optimise training stimuli for the jump shrug and hang high pull. Finally, additional literature has indicated that loads of approximately 90% of an athlete's 1RM power clean (Haff et al., 2003) or full clean/snatch (Ermakov, 1980) may optimise the training stimulus for the clean/snatch pull from the floor.

SPEED DEVELOPMENT

A sequenced progression of programming weightlifting derivatives may aid in the development of an athlete's speed characteristics (DeWeese et al., 2016). Using the methods described above, specific weightlifting derivatives may be programmed during specific strength training phases that coincide with speed development phases (Figure 15.16). The following will discuss the rationale of prescribing a sequenced progression of weightlifting derivatives to enhance an athlete's sprint speed.

General preparation phase

As displayed in Figure 15.10, the general preparation phase is focused on improving the accelerative abilities of an athlete. Coaches may choose to program resisted runs (i.e., inclines and towing) at this point to develop high propulsive forces into the ground, while in the weight room a strength-endurance phase serves to develop the athlete's work capacity and cross-sectional area in order to enhance their muscular strength and power in later training phases (Stone et al., 1982). As mentioned above, practitioners may program the clean/snatch pull to knee, pull from the floor, and shoulder shrug. Each of these movements can be used to strengthen the athlete's musculature at specific angles that relate to their posture during various acceleration phases. For example, the first pull requires athletes to start from a knee angle of approximately 90° and extend the knees to about 120°, angles that coincide with a sprinter's knee angles in the starting blocks (Cˇoh et al., 1998).

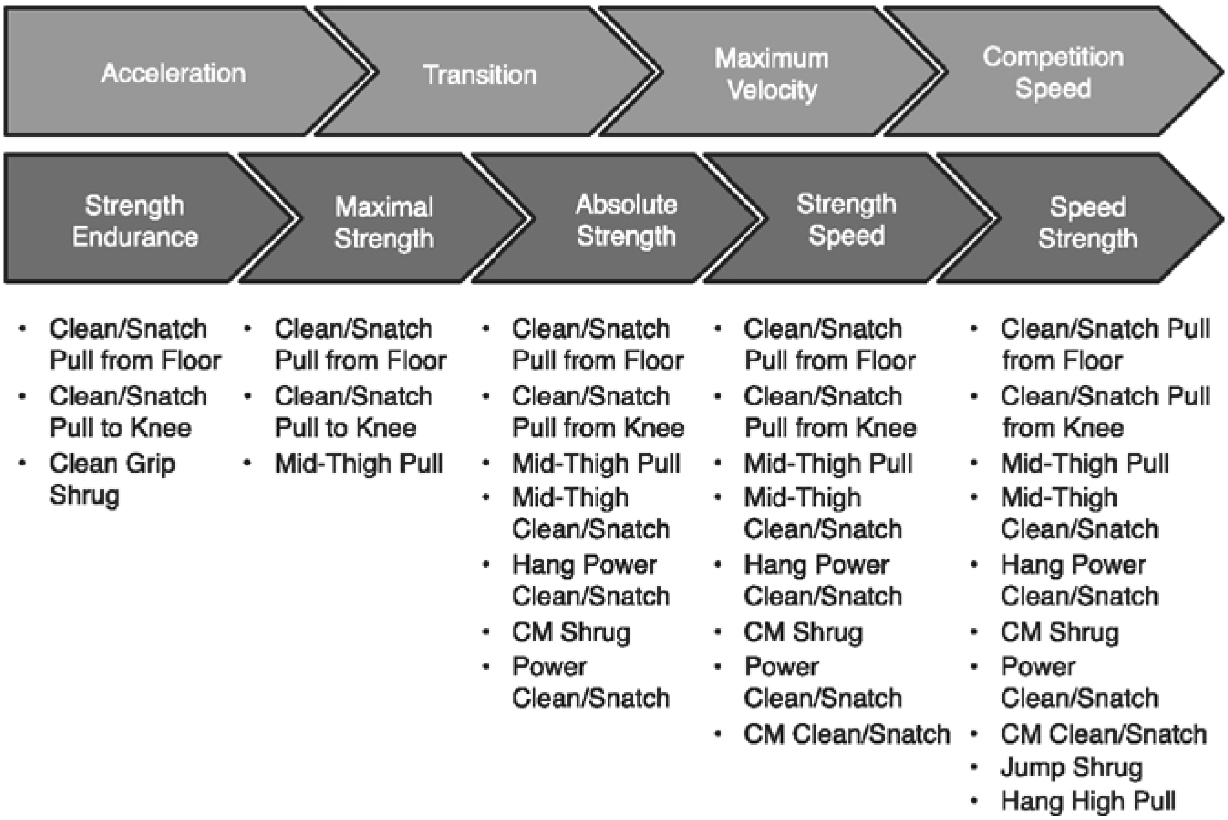

FIGURE 15.16 Sequenced progressions of speed and strength-power development with the weightlifting derivatives that may be used within each phase. Adapted from DeWeese et al. (2014).

Special preparation phase

Upon entering the special preparation phase of training, the training emphasis builds upon the enhanced acceleration characteristics from the previous phase to build top speed characteristics. Coaches may program running drills such as acceleration holds, low-load resisted runs, and longer segment accelerations during this phase before introducing maximum velocity sprinting drills (e.g., fly-in sprints and in-and-outs). Concurrently in the weight room, the focus of training shifts to improving the athlete's strength characteristics. The clean/snatch pull from the floor, pull from the knee, and mid-thigh pull exercises serve to develop vertical force production through the ranges of motion experienced during the acceleration and transition to upright running phases. Moreover, these movements overload the athlete in a position that is relative to top speed mechanics (i.e., 120–140° knee angle, tall torso, and shortened range of

motion) (DeWeese et al., 2015). In addition, exercises like the hang power clean/snatch, power clean/snatch, mid-thigh clean/snatch, and the full clean and snatch may be programmed during this phase to introduce a strength-speed component that will aid in the development of the athlete's RFD characteristics.

TABLE 15.1 Reported relative kinetic variables across power clean derivatives

Reference	*Subjects*	*PC (kg/kg)*	*Exercise*	*Force(N/kg)*	*RFD ($N.s^{-1}/kg$)*	*Power (W/kg)*
Comfort et al. *JSCR*. 26 (11): 2970–2974.2012	Collegiate Athletes (n=19)	1.07	PC (30% 1RM)	19.80	112.11	27.26
			PC (40% 1RM)	20.56	110.95	27.91
			PC (50% 1RM)	21.51	117.80	28.30
			PC (60% 1RM)	23.05	129.70	34.31
			PC (70% 1RM)	24.37	136.23	37.43
			PC (80% 1RM)	24.59	135.71	37.01
Comfort et al. *JSCR*. 27 (2): 363–368.2013	Female Collegiate Athletes (n=16)	0.83	MTPC (60% 1RM)	33.07	176.18	43.30
			MTPC (70% 1RM)	34.28	169.35	45.54
			MTPC (80% 1RM)	34.24	151.92	39.64
			HPC (PCK) (60% 1RM)	32.04	145.12	40.64
			HPC (PCK) (70% 1RM)	32.65	161.30	43.41
			HPC (PCK) (80% 1RM)	33.35	173.83	39.77
			PC (60% 1RM)	28.18	152.21	42.56
			PC (70% 1RM)	29.66	158.24	44.21
			PC (80% 1RM)	30.12	182.36	47.71
Comfort et al. *JSCR*. 25 (5): 1235–39.2011	Elite Rugby League Players (n=11)	1.19	MTP	30.75(26.76–34.76)	163.59 (88.65–204.08)	–
			MTPC	29.92 (26.21–32.57)	156.50 (88.04–232.10)	–
			HPC (PCK)	26.09 (22.62–32.88)	104.31 (65.15–210.23)	–
			PC	24.63 (21.74–28.07)	94.39 (59.88–154.27)	–
Comfort et al. *JSCR*. 25 (12): 3269–3273.2011	Elite Rugby League Players (n=16)	1.26	MTP	29.41 (26.03–32.79)	158.37 (95.76–220.97)	37.37 (30.94–43.79)
			MTPC	28.52 (25.25–31.79)	152.56 (94.13–210.94)	36.14 (28.40–44.22)
			HPC (PCK)	25.13 (22.07–28.20)	104.56 (69.78–139.31)	32.27 (26.94–37.66)
			PC	22.95 (20.35–25.56)	87.76 (56.31–119.21)	26.27 (17.17–37.97)
Comfort et al. *JSCR*. 26 (5): 1208–1214.2012	Collegiate Athletes (n=16)	1.05	MTP (40% 1RM)	35.45 (33.67–37.23)	244.30 (158.79–329.80)	52.40 (42.97–61.84)
			MTP (60% 1RM)	36.33 (34.48–38.17)	214.60 (143.78–285.42)	50.87 (44.26–62.57)
			MTP (80% 1RM)	36.44 (34.99–37.89)	240.83 (165.69–315.97)	45.72 (37.95–53.49)
			MTP (100% 1RM)	36.58 (35.19–37.96)	273.83 (191.95–355.70)	40.13 (36.16–44.10)
			MTP (120% 1RM)	37.84 (36.41–39.21)	370.14 (259.10–481.18)	38.62 (33.98–43.25)
			MTP (140% 1RM)	39.22 (37.29–41.15)	354.84 (255.49–454.20)	35.89 (29.43–42.34)

Comfort et al. *Sports Biomech.* 14 (2): 139–156	Male (n=10) & Female (n=10) Collegiate Athletes	Male – 1.08	MTP (40% 1RM)	41.40 (30.05–63.82)	–	67.43 (45.17–98.67)
			MTP (60% 1RM)	42.25 (30.64–65.48)	–	62.90 (37.30–88.39)
			MTP (80% 1RM)	42.22 (32.34–65.76)	–	55.96 (35.19–81.69)
			MTP (100% 1RM)	43.03 (31.77–68.45)	–	49.50 (33.67–65.75)
			MTP (120% 1RM)	43.89 (32.30–70.71)	–	45.66 (26.66–63.23)
			MTP (140% 1RM)	45.06 (32.31–73.52)	–	41.71 (24.21–55.68)
		Female – 0.71	MTP(40% 1RM)	30.86 (27.38–36.10)	–	42.00 (31.93–58.00)
			MTP (60% 1RM)	31.38 (28.67–37.48)	–	39.68 (30.83–55.00)
			MTPl (80% 1RM)	31.64 (28.00–37.48)	–	37.70 (29.68–50.21)
			MTP (100% 1RM)	32.13 (28.50–36.30)	–	34.81 (29.21–42.88)
			MTP(120% 1RM)	33.08 (29.20–39.02)	–	34.28 (29.17–41.03)
			MTP (140% 1RM)	34.59 (30.85–42.12)	–	33.15 (26.94–39.59)

Notes: MTP = Mid-Thigh Pull; MTPC = Mid-Thigh Power Clean; HPC = Hang Power Clean (PCK = Power Clean from the Knee); PC = Power Clean Range provided in (parentheses)

Early-mid competition phase

Leading into the start of the season, coaches will typically prescribe drills that will retain an athlete's accelerative and top speed abilities through short sprint work as well as training sessions specific to the sprint distances of the athlete's sport/event. Within the weight room, an early emphasis should be placed on strength-speed. Thus, weightlifting derivatives that focus on moving heavier loads quickly should be programmed. The suggested exercises within this phase include the mid-thigh pull and the power clean/snatch. The mid-thigh pull in this case will maintain high force production characteristics as practitioners may program up to 140% 1RM, while the power clean/snatch enables athletes to utilise the stretch-shortening cycle that occurs during the double knee bend as described above. The latter will allow athletes to generate large vertical forces in an upright position that may counteract those experienced during the stance phase of sprinting. Finally, the emphasis may shift to incorporating speed-strength exercises which move lighter loads quickly. Such exercises may include the countermovement clean/snatch, mid-thigh clean/snatch, hang high pull, and jump shrug.

Late competition/taper phase

Upon reaching the latter stages of competition, the emphasis in weight room training aims to emphasise speed-strength characteristics while retaining strength-speed characteristics. Practitioners may elect to

implement a variety of ballistic movements such as potentiation complexes, light-weighted jump squats, plyometrics, etc.; however, regarding weightlifting derivatives, the countermovement clean/snatch, mid-thigh clean/snatch, hang high pull, and jump shrug should be implemented during this phase of training. In addition, practitioners may consider implementing the mid-thigh pull to continue to retain strength-speed qualities. In fact, the mid-thigh pull could be programmed prior to one of the previously mentioned exercises in order to potentiate the power output of the latter exercise.

SUMMARY

Weightlifting movements and their derivatives are effective training tools that may be used to enhance an athlete's lower body 'explosiveness' and load absorption capacity. Weightlifting catching and pulling derivatives both provide useful training stimuli and may be programmed to meet the specific goals of various resistance training phases. A sequenced progression of weightlifting catching and pulling derivatives may be used to optimally develop the force-velocity profile and speed of an athlete.

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CHAPTER 16

Plyometric training

Christopher J. Sole

SECTION 1

Plyometric training (PT) is a classification of strength training exercise consisting mainly of various forms of jumping. These exercises are commonly integrated into a training process to enhance impulsive qualities of muscular performance such as speed-strength and reactive-strength. Depending on the goal of training, PT exercises may come in various forms. However, jumping exercises such as countermovement jumps, bounding, drop and depth jumps are some of the more common. Plyometric training however, is not limited to lower-extremity exercise, with various exercises developed for training the upper-extremities and trunk (Wilk et al., 1993, Potach and Chu, 2016).

Whether implemented independently or in combination with other training methods, PT has been found to enhance a variety of components of athletic performance such as jumping, sprinting, and change of direction ability (Booth and Orr, 2016, Markovic and Mikulic, 2010). Consequently, PT has become increasingly popular among strength and conditioning practitioners. However, in order to effectively incorporate PT into practice, practitioners must possess a basic understanding of the underlying science and empirical evidence supporting this training modality. Therefore, the purpose of this chapter will be to provide (1) a brief review of the mechanisms underpinning plyometric training, (2) a brief discussion of the physiological and performance adaptations elicited through plyometric training, and (3) an evidence-based discussion of the programing and periodization of plyometric training.

STRETCH-SHORTENING CYCLE

The coupling of eccentric and concentric muscle actions results in a natural function of muscle known as a stretch-shortening cycle (SSC) (Komi, 2000, Norman and Komi, 1979, Komi, 2008). During an SSC, the eccentric action enhances subsequent concentric action resulting in increased force, power, and efficiency, referred to as SSC potentiation. An SSC consists of three distinct phases: (1) the eccentric phase, (2) the amortization phase, and (3) the concentric phase. The eccentric phase is characterized by the active lengthening or stretch of the musculotendinous unit (MTU). The

amortization phase represents the brief time interval between eccentric and concentric muscle action and involves an isometric action. The concentric or propulsive phase consists of concentric muscle action. Plyometric training has become synonymous with an SSC (Wilt, 1978, Wilk et al., 1993), as SSC action is a key characteristic of all PT exercises. Therefore, a basic understanding of the mechanisms underpinning SSC potentiation/performance is crucial as they form the basis of all PT.

Several mechanisms of SSC potentiation have been proposed, and can be classified as either mechanical or neurophysiological in nature. The following will provide a brief review of these mechanisms, as a basic understanding of such is required for a complete discussion of the demands of PT. For an exhaustive review of the SSC and proposed mechanisms, see Chapter 3 and Turner and Jeffreys (2010).

From a mechanical perspective, SSC potentiation is attributed to the utilization of stored elastic energy. In this explanation, the MTU behaves similarly to a damped spring (Figure 16.1a) (Hill, 1938). During the eccentric action, or prestretch, energy is stored in the elastic components of the MTU then utilized in the following concentric action, ultimately enhancing force and power output. Multiple structures within the MTU collectively referred to as the series elastic component (SEC) and parallel elastic component (PEC) are capable of storing elastic energy. However, the SEC, namely tendon, is believed to be the primary contributor during SSC function (Kubo et al., 1999, Lichtwark and Wilson, 2005).

In addition to mechanical factors, several neurophysiological mechanisms have been suggested to explain SSC potentiation. Involuntary nervous processes such as the stretch reflex (Figure 16.1b) have been implicated in contributing to SSC potentiation (Dietz et al., 1979, Bosco et al., 1981). Briefly, the prestretch of the MTU initiates a reflex action via the muscle spindles. When the muscle spindles detect a rapid increase in muscle length, a neural impulse is relayed to the spinal cord via type Ia afferent fibers. Type Ia afferent fibers then synapse with the alpha motor neuron resulting in a reflexive muscle action (Kandel et al., 2000). If appropriately timed, it is believed the pairing of voluntary and involuntary (reflexive) actions results in supramaximal concentric activation of the agonist muscle.

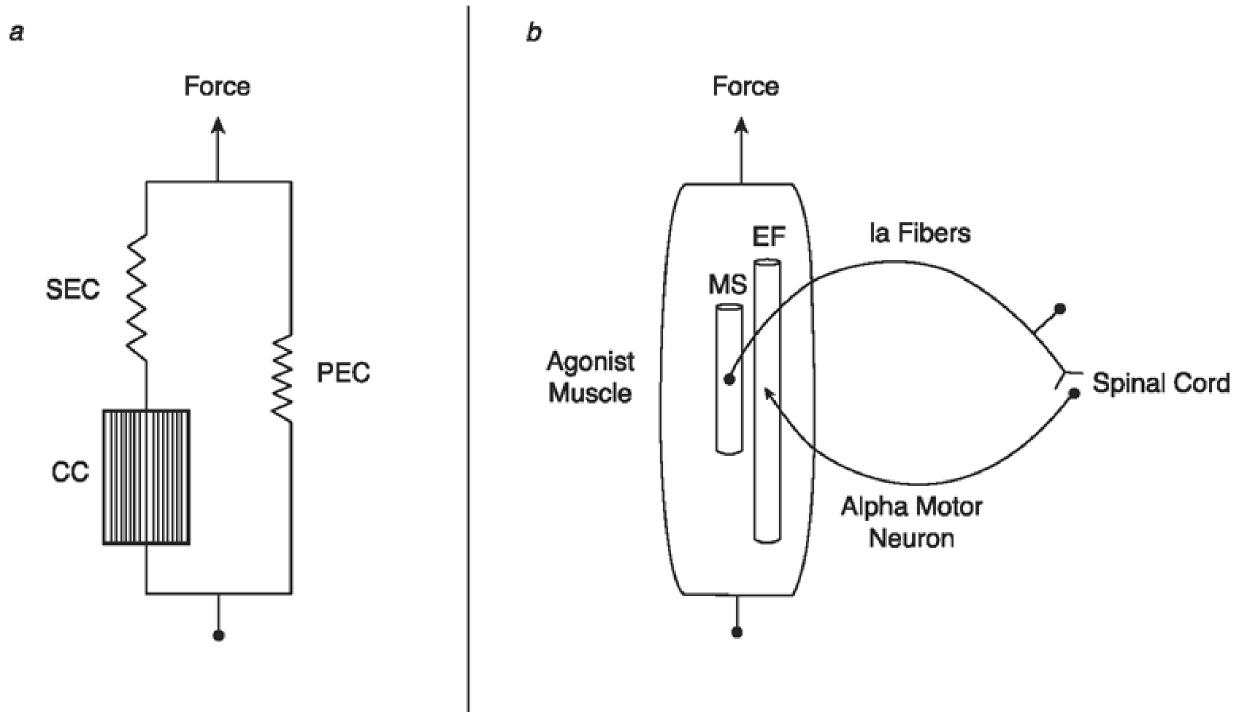

FIGURE 16.1 (a) Mechanical and (b) neurophysiological models of stretch-shortening cycle potentiation. SEC = series elastic component, CC = contractile component, PEC = parallel elastic component. MS = muscle spindles, EF = extrafusal fibers.

Additional theories have suggested that during SSC movements, the eccentric action of the prestretch results in an increase of the active state of the muscle (Bobbert and Casius, 2005), decreasing the time required to produce force by shortening the electromechanical delay or time interval between excitation and mechanical output (Cavanagh and Komi, 1979). This in turn results in an increase of the working range of the muscle, where greater force and impulse can be generated throughout the concentric phase of the movement. It has also been speculated that a prestretch and subsequent lengthening may place the muscle in a more optimal region of the length-tension relationship (Gordon et al., 1966a, Gordon et al., 1966b) resulting in improved force production at initiation and throughout concentric action (Ettema et al., 1992).

Although there still exists some debate over the exact mechanism responsible SSC potentiation, in general the potentiating effect of an SSC is likely attributed to a combination of these mechanical and neurophysiological properties of the neuromuscular system. However, the relative contributions of each mechanism in SSC potentiation remains unknown (Potach and Chu, 2016), and is likely to vary between exercises.

Relevant to both mechanical and neurophysiological perspectives is the time interval between prestretch and shorting, or amortization phase. In order for the stored elastic energy to be utilized, concentric action must immediately follow the stretch. If not, any energy stored in the elastic components will dissipate as heat. Similarly, too long of an interval between prestretch and concentric action will limit the contribution of the reflex action in concentric performance. An additional consideration is the rate and magnitude of the prestretch. A large and rapid stretch has been demonstrated to result in greater SSC potentiation and improved performance (McCaulley et al., 2007, McBride et al., 2008, Kilani et al., 1989, Váczi et al., 2013). Therefore, altering the prestretch through modifying characteristics of the exercise (e.g., velocity of descent, height dropped, etc.) may be viewed as one method for manipulating both the intensity and performance outcomes of PT exercises. The above consideration will be discussed in further detail in Section 2 as it relates to the application of PT.

ADAPTATIONS TO PLYOMETRIC TRAINING

Plyometric training interventions have been found to elicit a variety of neuromuscular adaptations related to enhanced SSC function and consequently enhanced athletic performance (Markovic and Mikulic, 2010). The following will review primary physiological and performance adaptations reported in the extant literature.

Plyometric training is most commonly associated with qualitative changes in muscle function. However, some evidence exists demonstrating quantitative improvements following PT such as whole muscle (Struminger et al., 2013, Chelly et al., 2010, Kubo et al., 2007, Vissing et al., 2008) and individual fiber hypertrophy (Malisoux et al., 2006a, Malisoux et al., 2006b, Potteiger et al., 1999), albeit predominantly in untrained individuals. For example, Malisoux and colleagues (2006a) reported increases in fiber diameter of 11% in type I, 10% in type IIa, and 15% in type IIa/IIx following a PT training intervention. From a qualitative standpoint, PT has been found to alter the contractile properties of individual fibers. Increases in peak fiber force of 19–35% in type I, 15–25% in type IIa, and 16–57% in type IIa/IIx fibers have been found following PT. Additionally, increases in maximal shortening velocity of 18%, 29%, and 22% were observed in type

I, IIa, and IIa/IIx, respectively (Malisoux et al., 2006a, Malisoux et al., 2006b). It is important to note that the alterations in contractile properties cited above were observed in addition to statistical improvements in lower-extremity functional performance, namely vertical jump, leg press, and shuttle run. Plyometric training is believed to result in a shift in muscle fiber type. However, limited evidence (Malisoux et al., 2006a) exists supporting this claim. Conversely, studies by Potteiger and colleagues (1999) and Kyröläinen and colleagues (2005) have suggested that fiber type transitions are not observed following PT alone.

In addition to adaptations to the muscle itself, performance improvements following PT may be attributed, at least in part, to adaptations to the nervous system. However, specific knowledge of the influence of PT on neural adaptation is limited. Proposed neural adaptations following PT include increased firing rate, motor unit recruitment, and reflex excitability, as well as improved inter-muscular coordination (Markovic and Mikulic, 2010). Furthermore, it is speculated that PT may reduce protective inhibitory reflex action originating from proprioceptors such as the Golgi tendon organ, resulting in improved performance under high-load conditions.

Muscular strength is a primary target adaptation of many training programs as it is believed to be a key component of many aspects of athletic performance (Suchomel et al., 2016). When implemented alone, PT has been found to increase strength in a variety of populations (Saez-Saez de Villarreal et al., 2010, Malisoux et al., 2006a, Vissing et al., 2008). These improvements are believed to be attributed to a combination of both neural and muscular adaptations (Markovic and Mikulic, 2010). However, as with muscular hypertrophy, an individual's training status may dictate the magnitude of strength adaptations following PT. For example, when examining the effect sizes reported in a metaanalysis by Saez-Saez de Villarreal and associates (2010), strength improvements following PT appear to be of a greater magnitude in lesser-trained individuals as compared to studies involving trained individuals. Muscular strength seems to be most affected when PT is implemented in combination with resistance training (Saez-Saez de Villarreal et al., 2013, Adams et al., 1987, Fatouros et al., 2000, Markovic and Mikulic, 2010, Booth and Orr, 2016). Although evidence does exist citing improved muscular strength, it is likely PT more strongly influences specific elements of strength such as reactive strength

and impulsive ability. For example, when comparing conventional resistance training with PT, Vissing et al. (2008) reported similar improvements in maximal strength between the two modalities; however, PT seemed to have a stronger influence on impulsive abilities such as countermovement jump performance and a ballistic-style leg press. Plyometric training and resistance training may also be combined within a single set. This pairing of high-intensity dynamic resistance training exercises with biomechanically similar PT exercises has been termed complex training (Ebben, 2002, Docherty et al., 2004).

Vertical jump is a fundamental athletic movement common in the performance of many sports, and PT has been demonstrated to improve vertical jump height in a variety of individuals across various types of vertical jump tests (Markovic, 2007, Saez-Saez de Villarreal et al., 2009). Previous literature, such as a meta-analysis performed by Markovic (2007), has cited mean improvements in jump height of approximately 5% in static and depth jumps, and up to 9% in countermovement jumps over training periods of 8.6 ± 2.7 weeks and 8.6 ± 3.4 weeks, respectively. Therefore, it seems adequate empirical evidence exists supporting the use of PT for improving jumping ability.

In addition to improving jump height, recent meta-analyses (Saez-Saez de Villarreal et al., 2012, Asadi et al., 2016) have provided evidence suggesting PT may be successfully implemented to enhance performance in other key components of sport performance such as sprinting and change of direction (COD) movements. For example, according to Saez-Saez de Villarreal and colleagues (2012), performing 80 high-intensity jumps two times per week over ten weeks was effective in eliciting improvements in sprint performance. Moreover, a meta-analysis performed by Asadi and colleagues (2016) concluded that performing moderate intensity PT including multiple forms of jumping is effective in improving COD ability over seven weeks. This result provides evidence demonstrating the key role of lower-extremity neuromuscular qualities such as SSC function (i.e., efficient coupling of eccentric and concentric muscle actions) in COD performance.

Interestingly, in addition to adaptations in strength and impulsive ability, PT has also demonstrated adaptations in neuromuscular efficiency such as improved running economy. Several studies have observed improvements in endurance performance following PT independent of any improvements

in aerobic fitness (Spurrs et al., 2003, Saunders et al., 2006, Turner et al., 2003). These performance improvements may be explained by an overall improved efficiency of the muscular system through improved eccentric-concentric coupling as well as more effective utilization of stored elastic energy. Therefore, performance benefits achieved through enhanced SSC performance are not limited to strength-power athletes.

Finally, considering the primary mode of PT is variations of jumping exercises, the bulk of the literature is focused on adaptations to the lower-extremities. However, several upper-extremity PT exercises have been developed (Wilk et al., 1993), including ballistic push-up variations, medicine ball throws, and depth push-ups (Potach and Chu, 2016). Although there is a paucity of research investigating upper-extremity PT, some empirical evidence does exist supporting the effectiveness of upper-extremity PT (Carter et al., 2007, Schulte-Edelmann et al., 2005).

SECTION 2: PRACTICAL APPLICATION OF PLYOMETRIC TRAINING

As illustrated in Section 1, integrating PT into an athlete's training program can result in the enhancement of various aspects of athletic performance including improved jumping, sprinting, and change of direction ability. However, for effective implementation of PT, practitioners must possess adequate knowledge of programming including methods of appropriate progression, variation, and overload of PT. Furthermore, effective programing must take into consideration the athlete's needs, training history, and most importantly, how this training modality fits into the broader picture that is the training process.

MODE AND SPECIFICITY OF PLYOMETRIC TRAINING

An initial step in the programing of any exercise is identifying the most appropriate mode of training. The mode of PT exercise must be carefully selected based on the demands of the sport and/or player position, as well as the needs and history of the individual athlete. In general, PT can be divided into lower-extremity, upper-extremity, and trunk exercises (Potach and Chu, 2016). In many cases one may implement only one mode of PT (e.g., lower-extremity), on the other hand, a practitioner may determine several modes of PT are appropriate for their athlete(s). Examples of common PT exercises are provided in Table 16.1.

Specificity of training is among the most important considerations when designing a training program, as the most specific training exercises should result in the greatest transfer of training effect. Commonly, an exercise's specificity is determined through "face validity" or the outward appearance of the gross mechanics of the exercise, rather than the specific adaptations that are required. In order to choose the most appropriate methods of progression, overload, and variation, practitioners must possess a thorough understanding of the impact of specificity on PT. In addition to the gross mechanics of the movement, practitioners should consider the magnitude of the forces produced, rates at which forces are developed, velocity and acceleration characteristics, and temporal characteristics of the exercise (Stone et al., 2007). Although specificity is crucial to adaptation, overly

specific training, which is not specific to the required adaptive response, can also lead to deleterious training stimuli. For example, one may sacrifice speed of movement or rate of force development in effort to mimic a highly specific sporting movement.

An example the role of specificity in transfer of training is provided by Nagahara and associates (2014) who examined the relationships between acceleration during a 60-meter sprint and various jumping tasks. The analysis revealed markedly different correlation coefficients when comparing jumping tests and acceleration across each phase of the sprint. For example, the static jump was most strongly related to early acceleration phase, whereas the ankle jump (a continuous rebound jump performed using only plantar flexion) was most strongly related to maximum velocity sprinting. In other words, the kinetic and kinematic characteristics of exercise must be carefully examined to ensure they are in line with the mechanical characteristics of the movements you are trying to enhance. Consider an additional example, a typical ground contact time during the high jump take-off is ≈ 175 ms (Aura and Viitasalo, 1989). If given the choice between a countermovement jump and a drop jump as a training exercise, the drop jump would be the most appropriate, as contact times for this exercise are ≈ 136–222 ms (Walsh et al., 2004) as compared to a movement time > 250 ms (generally 400–600 ms) experienced in the countermovement jump. Moreover, the characteristics of the prestretch between these two exercises are drastically different, with a much greater rate and magnitude of stretch experienced during the drop jump.

An often overlooked element of specificity relates to the instructions and coaching cues given during training. Motor learning research has indicated that instructions regarding the goal and attentional focus of the exercise can markedly influence performance outcomes (Hodges and Franks, 2004, Wulf, 2007). Application of this element of specificity has been recently highlighted in a review of coaching cues for sprinting (Benz et al., 2016). Specifically related to PT, studies have reported instructions to be a key factor influencing the kinematic and kinetic characteristics of the several common PT jumping exercises (Young et al., 1995, Talpey et al., 2016, Louder et al., 2015). Talpey and colleagues (2016) reported that instructing participants to “minimize ground contact time” as compared to “maximize jump height” in the depth jump resulted in not only decreased ground contact times, but also increased peak force, mean acceleration, and

propulsive impulse during the exercise. Consequently, ensuring proper instructions are provided during PT should be a key specificity consideration, as it can have an impact on the stimulus and resultant adaptation of the exercise.

TABLE 16.1 Examples of common plyometric training exercises

Mode		*Exercises*	*Intensity*
	Stationary jumps	• Ankle hop (bilateral and unilateral) • Squat jump • Countermovement jump • Split jumps	• Low • Low • Low • Low/moderate
	Standing jumps	• Broad jump • Static jump over barrier • Countermovement jump over barrier	• Moderate • Moderate • Moderate
	Lower-extremity Multiple jumps/bounding	• Hops (bilateral and unilateral) • Repeat broad jump • Alternate-leg bound • Power skip • Single-leg bound • Side skip • Zig-zag bound (speed skaters)	• Low • Low-moderate • Moderate/high • Moderate/high • High • Low/moderate • Low/moderate
	Box jumps	• Static jump onto a box • Countermovement jump onto a box • Land and stick • Depth jump • Drop jump • Depth jump to Box • Depth jump over barrier	• Moderate • Moderate • Low-moderate • High • High • High • High
Upper-extremity		• Chest pass • Underhand toss for height	• Moderate • Moderate

	• Single-arm chest pass • Depth push-up	• Moderate/high • Moderate/high
Trunk	• Delivery toss • Chop • Sit-up throw	• Moderate • Moderate • Low/moderate

FREQUENCY AND RECOVERY

Training frequency is typically expressed as the number of training sessions per microcycle (week). As with all training, the frequency of PT will vary depending on the specific phase of the training year. Factors influencing PT frequency include: primary focus of the training phase, competition schedule, and proportion of training time devoted to sport practice, among others. Limited research exists as to optimal PT frequency. However, based on the results of meta-analyses investigating jumping (Saez-Saez de Villarreal et al., 2009), sprinting (Saez-Saez de Villarreal et al., 2012), and change of direction (Asadi et al., 2016) totaling 106 studies, two sessions per week appears to be a sufficient training stimulus.

In addition to the aforementioned factors, PT frequency is ultimately determined by between-session recovery time. Considering the high-intensity nature of PT, between 48 and 72 hours has been suggested as an appropriate recovery time between sessions. Therefore, between two and three PT sessions per microcycle seems to be the upper limit. It is important to note that recovery time from PT sessions may be highly variable based on several factors. The volume, intensity, as well as individual athlete factors such as training status should be considered when deciding optimal recovery. Moreover, many sports are inherently “plyometric” such as basketball, volleyball, and netball. This presents a logistical problem for practitioners attempting to appropriately program PT sessions while taking into consideration recovery from both practice as well as previous training sessions. Therefore, it is highly recommended that practitioners carefully track volume and intensity of both training and sport practice as well as implement monitoring interventions in order to judge recovery and ensure an optimal training stimulus.

Recovery within the training session itself, or intraset and interset recovery interval, is also an important programing consideration. When determining the intraset and interset recovery periods, the practitioner should again consider the volume and intensity of the training exercise. Although by definition most PT exercises are high intensity, some are performed at a lower intensity and therefore may require less recovery. For example, the interset and intraset recovery when performing low-amplitude bilateral hops would be much less than when performing a set of 40cm drop jumps considering the marked differences in kinetic and kinematic characteristics between the two exercises (Figure 16.2). In general, the practitioner should keep in mind the overall goal of PT, which is to enhance impulsive and reactive qualities. Therefore, each repetition should be performed in a high-quality manner. General recommendations for work to rest ratios for PT range from 1:5 to 1:10 depending on the specific exercise (Potach and Chu, 2016).

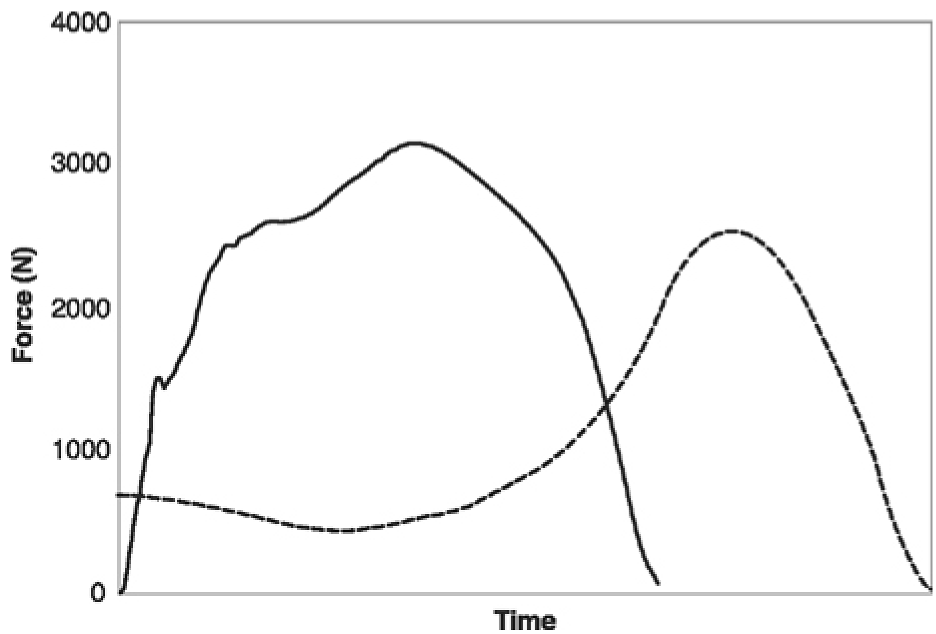

FIGURE 16.2 Illustrates the force-time histories of a bilateral ankle hop (dashed line) and a drop jump from 40 centimeters (solid line). Note the differences in rate and magnitude of force production as well as impulse (area under the curve) between the two exercises.

VOLUME AND INTENSITY

In traditional resistance training the most commonly used measures of training "dosage" are volume and intensity. Training volume refers to the amount of work performed by the athlete during training, and can be quantified for a set, session, week, etc. Several methods of quantifying PT volume have been suggested (Potach and Chu, 2016, Chu, 1998). In general, the simplest methods are usually the most practical. For example, in horizontal PT exercises (e.g., alternate-leg bound, single-leg bound) volume can be expressed as the total distance covered during the session. Using this method, a set of four alternate-leg bounds performed over 25m would result in a total volume of 100m. Although this method may be sufficient, it would be difficult to equate across athletes on account of differences in limb length and ability. A more effective method may be to express volume as the total number of ground contacts, or throws/catches in upper-extremity, and trunk exercises. Counting contacts or throws is also preferable considering a large number of PT exercises are performed in place (Table 16.1). When prescribing PT volumes, factors such as experience level and specific training focus should be carefully considered. If prescribing based on experience level, experts have suggested between 80–100, 100–120, and 120–140 contacts per session for beginners, intermediate, and advanced athletes, respectively (Potach and Chu, 2016). It should be noted, however, that the primary factor determining volume would be exercise intensity, with an inverse relationship existing between the two training components.

Training intensity is typically indicative of the rate of work performed during an exercise. However, in PT it can also be related to the mechanical demands (rate and magnitude of loading) placed on the associated musculature during the exercise. Intensity of PT can be indirectly quantified in a variety of ways. In many cases intensity is inherent to the specific exercise. General guidelines for determining the intensity of a specific exercise include (1) the speed of the movement, (2) the points of contact (i.e., single vs. double leg hopping), (3) the amplitude of the movement, and (4) the body weight of the athlete or amount of added resistance (Turner and Jeffreys, 2010, Jeffreys, 2007). Approximate intensity levels are provided for the exercise listed in Table 16.1. Recently, with the increased availability of technology such as force platforms, authors have suggested using the movement's kinetics as the most valid method for objectively quantifying and tracking the demands of PT. Using this approach, variables

such as peak force and rate of force development can be used to gauge exercise intensity, whereas impulse may be used to quantify volume (Jarvis et al., 2016).

When it comes to manipulating intensity, the practitioner can choose from variety of options. Common methods for manipulating intensity include: manipulating jump height or box height in the case of box jumps and drop and depth jumps, the addition of an external load, or manipulating the speed of the movement and/or rate at which work is performed (e.g., jumps/throws per minute). Considering some PT exercises are inherently more intense than others, perhaps the simplest method of manipulating exercise intensity is changing the exercise itself. Careful attention should be placed on appropriate increases in intensity, as increasing the intensity beyond a certain level may alter the movement and training stimulus. In many cases, standards can be identified and intensity can be prescribed relative to maximum or criterion performance outcome such as peak power output (Di Giminiani and Petricola, 2016) or maximum jump height (Chu, 1998). Jumping exercises can also be performed effectively using added resistance such as a weighted vest (Khlifa et al., 2010). However, there is limited evidence supporting the effectiveness of loaded PT. It is important to note, however, that PT is high-intensity in nature, thus reducing the intensity of an exercise below a specific threshold may result in an unintended training stimulus. Conversely, inappropriate increases in intensity may unintentionally alter the exercise, such as increasing ground contact time or altering movement mechanics. Therefore, the practitioner must exercise caution when manipulating PT intensity and pay close attention to the quality of the movement ensuring that it is not sacrificed as intensity increases.

PROGRESSION

Proper progression and variation of PT exercise is a key factor of effectively implementing PT, in addition to the more commonly known rationale for progression and variation: avoiding monotonous training and staleness. A traditional approach would be to progress from more general low-intensity to more specific high-intensity PT exercises. Progression plays a key role teaching athletes effective mechanics, which is believed to influence the safety and effectiveness of PT. For example, Turner and

Jeffreys (2010) suggest a specific progression for beginners focusing on first jumping then landing and load absorption mechanics before complete SSC movements are performed.

The general consensus is that if appropriately implemented, PT is safe for most individuals including adolescents. However, due to the high-intensity nature of PT, several training texts have outlined pre-training considerations to be addressed prior to implementing PT, most notably learning proper landing mechanics (Potach and Chu, 2016). Interestingly, several authors have also suggested one should possess a relative strength level equivalent to a back squat of 1.5 × bodyweight prior to initiating lower-extremity PT (Potach and Chu, 2016). Although controversial, this recommendation may be viewed as intuitive from an injury prevention standpoint (Radin, 1986). Furthermore, evidence suggests that increasing strength may optimize PT performance and therefore adaptation (Barr and Nolte, 2014, Suchomel et al., 2016). Overall the practitioner should use their judgment in determining whether or not the athlete is prepared to initiate PT.

PERIODIZATION OF PLYOMETRIC TRAINING

Periodization can be broadly defined as the planned distribution and variation of training stimuli in order to maximize fitness and improve the likelihood of competitive success. When considering periodization strategies for PT, practitioners should be reminded that effective periodization involves the integration of all training modalities into a complimentary sequence (i.e., the training process). Therefore, the following will discuss basic considerations for the proper progression and periodization of PT in context of the training process. Furthermore, considering empirical data from long-term training studies involving multiple mesocycles are scarce, much of the following information has been deduced from multiple studies and expert intuition.

Given its high-intensity nature, focusing on PT year-round would be inappropriate. Furthermore, fatigue can have profound effects on SSC performance, negatively impacting mechanical characteristics of the movement and likely altering the training stimulus. Consequently, PT may best be implemented in training phases where overall training volume is low and there is an emphasis on movement quality (e.g., strength, and

impulsive “explosive” phases). However, PT may be used in high-volume training phases to familiarize the athlete with PT and progress technique, perhaps through integrating low-intensity PT into elements of the training preparatory routine, with jump training-based warm ups shown to improve lower-extremity landing mechanics, which may reduce injury risk (Herrington, 2010, Myer et al., 2012, Herrington et al., 2015, Herrington and Comfort, 2013).

A key component of periodization is the logical and complimentary sequencing of training phases and fitness characteristics. With this in mind, information from several sources promotes emphasizing strength and maximal strength through heavy resistance training (> 85% 1RM) prior to PT in order to maximize the net effectiveness of this training modality. The adaptations to the MTU experienced following heavy resistance should result in optimized stiffness and force generation in subsequent PT. Additionally, an increase in strength of muscle and connective tissue should reduce the likelihood of injury.

In addition to optimizing acute performance and reducing the likelihood of injury, evidence suggests that emphasizing strength training prior to PT may maximize the net effectiveness of the overall training process. Briefly, according to data provided by Minetti (2002) and Zamparo and colleauges (2002), if impulsive ability or “explosiveness” is the target training adaptation, this type of training (i.e., PT) should be preceded by blocks of strength-focused training, where strength-endurance, hypertrophy, and maximal strength are the primary training emphasis. In other words, optimizing adaptation to PT can be achieved through a specific sequence of complementary training phases (Figure 16.3). This model of training is based on the concept of phase potentiation and has been integrated in several periodization schemes (Stone et al., 2007, Harris et al., 2000, Bompa and Haff, 2009).

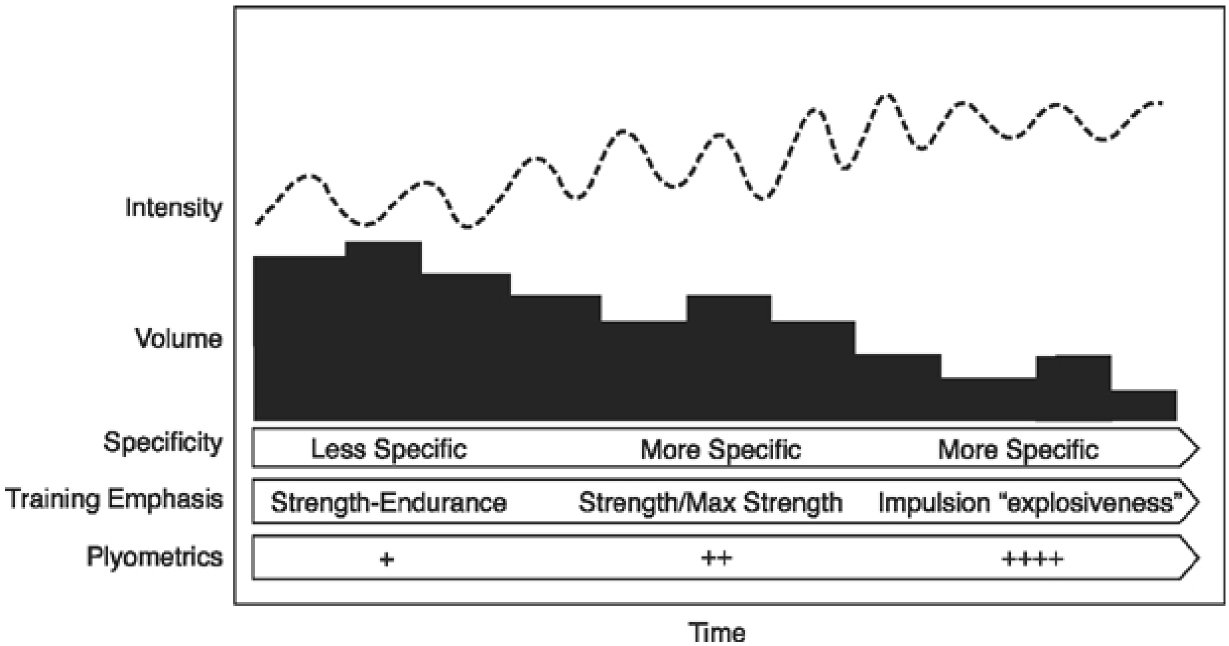

FIGURE 16.3 Illustration of a generic periodization model where the target training adaptation is impulsive ability or "explosiveness". Note the emphasis on plyometric training is greatest during periods of low-volume and high-intensity training. Additionally, plyometric training is emphasized following periods of strength and maximum strength focused training.

Collectively, we can conclude the following related to the integration of PT in one's periodization scheme: (1) to maximize effectiveness, PT should be emphasized during periods of training where fatigue is low and movement quality is emphasized, (2) based on the available evidence, it appears performing heavy resistance training prior to PT should maximize performance and reduce the risk of injury, and (3) if the ultimate training goal is to maximizing impulsive ability or "explosiveness", emphasizing strength and maximal strength prior to focused PT training will likely result in the greatest net training effect. Examples of how to structure PT sessions for different mesocycles are presented in Figures 16.4–16.6.

SUMMARY

- Plyometric training is a form of explosive resistance training comprised of various jumping and throwing exercises.
- As nearly all plyometric training exercises are considered to involve a stretch-shortening cycle, knowledge of the underlying mechanisms of

this muscle function will aid the practitioner in effectively implementing plyometric training.

- A large body of empirical evidence exists supporting the effectiveness of plyometric training in enhancing a variety of elements of athletic performance.
- Practitioners considering adding plyometric exercises into their athlete's training should not only consider the basic principles of training, but also possess an understanding of how this training modality can be integrated into the training process as a whole.

General Preparation Phase: Strength-Power Athlete

Week	1	2	3	4	5	6	7	8
Ankle Hop	3 × 10	3 × 10	3 × 10	3 × 10				
Lateral Hop	3 × 10	3 × 10	3 × 10	3 × 10				
SJ to Box	4 × 5	4 × 5	4 × 5	4 × 5	5 × 5	5 × 5	5 × 5	5 × 5
CMJ to Box	4 × 5	4 × 5	4 × 5	4 × 5	5 × 5	5 × 5	5 × 5	5 × 5
Broad Jump to Stick					3 × 5	3 × 5	3 × 5	3 × 5
Repeat Broad Jump					3 × 5	3 × 5	3 × 5	3 × 5
Frequency	2	2	2	2	2	2	2	2
Volume (Jumps/Contacts)	100	100	100	100	80	80	80	80
Intensity	Low				Low – Moderate			

FIGURE 16.4 Displays a generic example of how PT may be programed during a general preparation or strength-endurance mesocycle(s). In this example, the primary role of PT is to facilitate the learning of proper technique through exposing the athlete to a progression of simple exercises. In turn, general work capacity is established as well as a foundation for more advanced and higher intensity PT exercises. Plyometric training during this phase could be easily integrated into the warm up routine. Depending on the overall goals of the training process, as well as the training history of the athlete(s), a PT program such as this may not need to span eight weeks.

Strength Phase: Strength-Power Athlete

Week	1	2	3	4	5	6	7	8
Skip for Height	3 × 10+10	3 × 10+10	3 × 10+10	3 × 10+10				
Skip for Distance	3 × 10+10	3 × 10+10	3 × 10+10	3 × 10+10				
SJ Med Ball Toss (Height)	5 × 5	5 × 5	5 × 5	5 × 5	5 × 3	5 × 3	5 × 3	5 × 3
Drop to Stick	5 × 5	5 × 5	5 × 5	5 × 5	5 × 3	5 × 3	5 × 3	5 × 3
CMJ Med Ball Toss					5 × 5	5 × 5	5 × 5	5 × 5
Hurdle Hop					5 × 5	5 × 5	5 × 5	5 × 5
Frequency	2	2	2	2	2	2	2	2
Volume (Jumps/Contacts)	110	110	110	110	80	80	80	80
Intensity	Moderate				Moderate – High			

FIGURE 16.5 Displays a generic example of how PT may be programed during a basic or maximum strength mesocycle(s). The athlete is progressively exposed to increased stretch and loading conditions in order to prepare for higher intensity PT exercises aimed to fully exploit SSC potentiation. As force production capacity improves, PT exercises progress from partial to more complete SSC movements. Considering training volume and intensity are typically high during strength-focused mesocycles, practitioners must carefully plan the integration of PT into the training process.

Impulsion "Explosiveness" Phase: Strength-Power Athlete

Week	1	2	3	4	5	6	7	8
Power Skip	3 × 10+10	3 × 10+10	3 × 10+10	3 × 10+10				
Depth Jump	4 × 5	4 × 5	4 × 5	4 × 5				
Alt-Leg Bound	4 × 5+5	4 × 5+5	4 × 5+5	4 × 5+5				
Ankle Hops	3 × 10	3 × 10	3 × 10	3 × 10	3 × 10	3 × 10	3 × 10	3 × 10
CMJ and Reach					5 × 5	5 × 5	5 × 5	5 × 5
Drop Jump onto Box					5 × 3	5 × 3	5 × 3	5 × 3
Frequency	2	2	2	2	2	2	2	2
Volume (Jumps/Contacts)	100	100	100	100	70	70	70	70
Intensity	High				High			

FIGURE 16.6 Displays a generic example of how PT may be programed during a mesocycle(s) where the primary training focus is developing impulsive ability or "explosiveness". In this phase the primary focus of PT is to exploit SSC potentiation in order to provide a maximal training stimulus. Plyometric training exercises may also be paired with other resistance training exercises in the form of complex training. Intensity should remain high throughout and volume may fluctuate depending on the training process as well as sport practice and training schedules.

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CHAPTER 17

Training change of direction and agility

Sophia Nimphius

INTRODUCTION

The athletic ability demonstrated when rapidly changing direction is considered a highly advantageous quality in an athlete, particularly but not limited to evasion sports both on the field or court. However, despite the increasing research into change of direction ability from a performance and injury perspective, there is still little consensus on the development of this ‘elusive’ physical quality. However, there has been a substantial advancement in the understanding of the biomechanical underpinnings of changing direction and the influence of perceptual-cognitive factors that combine for the perceptual-motor response known as agility.

This chapter aims to provide an overview of the current research and scientific understanding of factors associated with change of direction and agility with respect to biomechanical, physical and perceptual-cognitive determinants (Section 1). In Section 2, an applied understanding of how to quantitatively and qualitatively evaluate change of direction ability and agility will be examined, followed by an example of a needs-based program in conjunction with a developmental framework designed to combine improvements in physical capacity with skill development.

SECTION 1

DEFINITIONS

Over the last two decades, more clarity on definitions associated with change of direction research has culminated. However, there is still ambiguity of term use both in the research and applied fields. Therefore, the current chapter will use the following definitions and terms in addition to their abbreviations.

Change of direction (COD) – the skills and abilities needed to change movement direction, velocity or modes (DeWeese and Nimphius, 2016). Describes the **physical event of changing direction** and may be used independent of the situation (e.g., ‘pre-planned’ or ‘reactive’) as ultimately a COD still occurs. The COD may be further defined as the events that occur just prior (entry), at the ‘plant’ (occurring between entry and exit) and just following (exit) when describing the typical ‘cutting’ COD movement. This will form the focus of the biomechanical analysis of COD section of this chapter.

Change of direction speed (CODS) – overarching description of any test that proposes to examine one’s ‘pre-planned’ COD ability (e.g., T-test, 505, Illinois agility test, pro-agility test) that often has a large component of straight line running.

Maneuverability – a further delineation of COD where the purpose of the change in direction is to maintain velocity, therefore eliminating a clearly defined ‘plant’ step associated with a ‘cutting’ COD and subsequently eliciting a more curvilinear path of movement. Further, maneuverability may also be used to describe a COD when one changes mode of travel and the purpose may be tactical movement preference (e.g., COD into a backpedal or shuffle) (Nimphius et al., 2017, Nimphius, 2014).

Agility – ‘a rapid whole-body movement with change of velocity or direction in response to a stimulus’ (Sheppard and Young, 2006). As

such, an agility maneuver is predicated on a stimulus-response, but the subsequent movement may take the form of any of the aforementioned methods by which one changes direction.

BIOMECHANICS OF CHANGING DIRECTION

Although the biomechanics of changing direction could be considered complex, the principles that govern human motion allow for a narrowing of the critical factors required for rapid and efficient COD. Therefore, the commonly measured variables of velocity, force, impulse, ground contact time and momentum can provide a comprehensive understanding of the critical factors relevant to changing direction. With a sound biomechanical understanding, one has the fundamental knowledge required to better understand the interaction of physical capacity and technical or skill requirements that must be present in combination to maximize any COD performance. To begin this discussion of the biomechanics during a COD, a ground-up approach will be adopted, commencing with a description of impulse and ground contact times, followed by a discussion on joint kinematics and kinetics associated with a COD.

Understanding impulse and ground contact times during a change of direction

The ‘plant’ phase, which as previously described, is the step that is most unique in comparison to the mechanics associated with sprinting. Although the plant step is still a stance phase, the term ‘plant’ is chosen to differentiate it from other steps. Specifically, the plant phase is distinctive as it is the instance of transition often including both a braking and propulsive component with typically longer (and intentional) deceleration (braking) followed by acceleration (propulsive) within the force-time (or impulse) curve as shown in Figure 17.1 in comparison to the stance phase during sprinting. However, the plant phase during a COD will vary depending on the velocity of entry (Nedergaard et al., 2014) and the angle of required change of direction (Havens and Sigward, 2015b), which may result in an increase or decrease in the ground contact time for which the plant phase occurs.

Therefore, as one considers the different shapes of the curves shown in Figure 17.1, one can also appreciate the different magnitudes and durations of impulse which determine the subsequent change in momentum and therefore velocity as defined by the impulse-momentum theorem. The height of the impulse curve represents the amount of force produced during the plant phase, whereas the width of the impulse curve determines the time one has to apply this force (associated with the rate of force development within the context of a COD). As such, the magnitude of force required or produced and the time available for producing this force can subsequently be used to understand the physical requirements to perform the COD. Further, the change in momentum and subsequent velocity and actual angle of COD that results will be a function of the direction of force application, and the effectiveness of the produced impulse will be expected to be similar to that of sprinting (Rabita et al., 2015). Examples of the time available or time required to execute various changes of direction are described in Table 17.1. As the angle of COD increases, the ground contact time often increases, providing differences in time available to create force that could be considered analogous to comparing time available for a countermovement jump versus a drop jump (Nimphius et al., 2017).

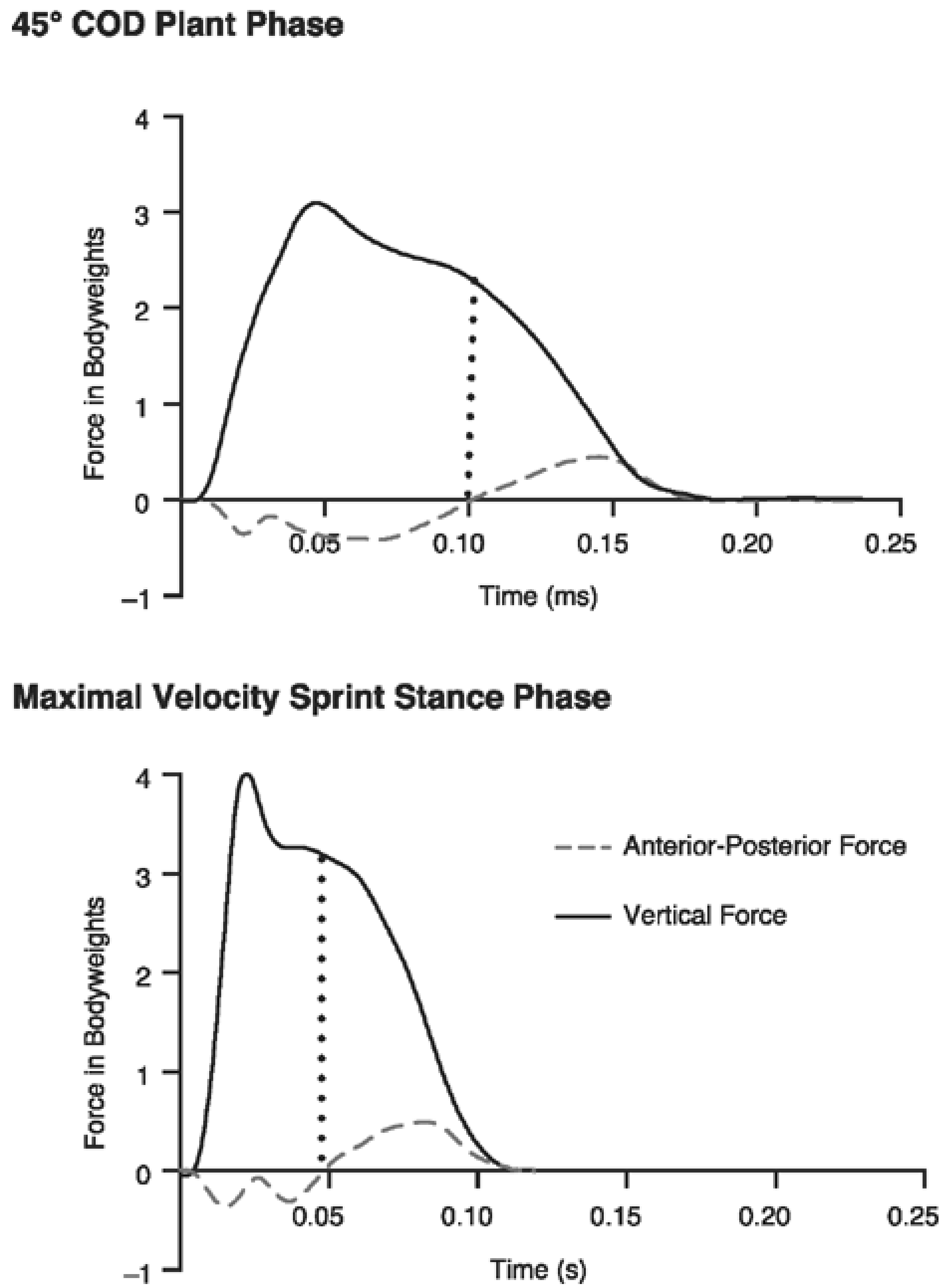

FIGURE 17.1 Example of force-time curve of the plant phase of a 45° COD and a stance phase of a maximal velocity sprint. The vertical dashed lines represent the distinction between the braking and propulsion phases as defined by the anterior-posterior force. Further, notice the difference in the length of these phases and the total ground contact time. The total area under each curve is the impulse.

However, it should be understood that a proportion of the deceleration often occurs prior to the plant step (e.g., penultimate step or prior) (Nedergaard et al., 2014, Havens and Sigward, 2015b), explaining why the plant step doesn't always fully quantify the demand of greater angle

directional changes or why some directional changes can have equal or lesser ground contact times than more shallow changes of direction. For example, substantial braking in the steps prior to the plant step have been shown prior to 135° COD (Nedergaard et al., 2014) and 180° COD (Graham-Smith et al., 2009). The prior deceleration is likely a strategy to decrease the difficulty and ground contact time spent changing direction, otherwise ground contact times may extend as shown to occur when prior deceleration is not possible as with a sudden response to a stimulus (Spiteri et al., 2015a) and shown in Table 17.1. Further, additional acceleration occurs following the plant step, which is critical to subsequent success following the COD.

TABLE 17.1 Ground contact times during various angles of change of direction

Reference	*Description of change of direction*	*Mean ground contact times (s)*
(Havens and Sigward, 2015b)	~ 45° COD during planned task	0.16
(Vanrenterghem et al., 2012)	~ 45° planned task (measured actual angles 39.5° to 25.5°) at various velocities (between 2 m.s^{-1} to 5 m.s^{-1}); as velocity increased angle of actual performance decreased and ground contact time decreased	0.20–0.45
(Spiteri et al., 2014a)	~ 45° COD during agility task from both offensive and defensive conditions with human stimulus	0.23–0.26
(Spiteri et al., 2015a)	~ 45° COD during agility task with video stimulus	0.42–0.51
(Marshall et al., 2014)	~ 75° COD during planned task	0.37
(Havens and Sigward, 2015b)	~ 90° COD during planned task	0.25
(Spiteri et al., 2015a)	~ 90° COD during planned task with transition into a shuffle	0.32–0.35
(Spiteri et al., 2015a)	~ 180° COD during planned task	0.42–0.47

One may, therefore, have to consider the steps entering, the characteristics of the plant step and the steps exiting a COD when assessing the biomechanics of performance, while still ensuring the assessment

appropriately isolates the biomechanics surrounding the actual COD instead of a re-evaluation of sprint acceleration ability. As discussed by Havens and Sigward (2015b), the approach step (penultimate step) and execution step (plant step) have significantly slower velocities during a 90° COD than during a 45° COD. Therefore, biomechanical factors such as velocity of entry and angle of COD have clear implications for differences in physical requirements for the different ranges of COD performance required in sport. This will be discussed later in this chapter.

Although largely not discussed in research (Nimphius et al., 2017), the mass of the athlete should be considered in addition to the aforementioned critical factors of velocity and angle of change of direction. More recent research has highlighted the consideration for calculating what is termed 'sprint momentum' for rugby athletes whereby the maximal velocity of an athlete is multiplied by their body mass to determine their momentum, which is considered influential for aspects of sport performance such as breaking tackles (Hendricks et al., 2014, Baker and Newton, 2008). Therefore, within the context of a COD, the velocity of the athlete exiting a COD or the momentum an athlete carries into a COD (entry velocity multiplied by body mass) are factors that practitioners should consider within the biomechanical requirements of an individual athlete's performance, when applicable.

Joint kinematics and kinetics during a change of direction

The discussion of joint kinematics and kinetics during a COD with respect to injury risk has been researched extensively in the literature (Kristianslund et al., 2014, McLean et al., 2004, Jones et al., 2015, Imwalle et al., 2009). However, there is acknowledgement that some joint positions that may create unfavorable loads with respect to injury risk may also be advantageous for performance (Jones et al., 2015) or necessary for task completion (Havens and Sigward, 2015a), but this has yet to be fully understood. Further complications arise when understanding that although expected changes in whole body centre of mass (COM) occurs when comparing a more shallow COD (45°) versus a more aggressive COD (90°), simultaneous increased physical demand is not evenly evident across all joints (Havens and Sigward, 2015a). Of critical understanding from the research of Havens and Sigward (2015b) is the unique finding that the

deceleration demand of the 90° COD in comparison to the 45° COD resulted in different hip functions where the hip seemed to primarily stabilize the trunk during the 90° COD. Further, the aforementioned research highlighted differences in these two COD demands where far greater pelvis rotation occurred during the 90° COD and a trend to larger moments and power absorption at the knee (Havens and Sigward, 2015a) also occurred, likely in response to the increased deceleration demand and hip control requirements in handling the increased trunk lean during the 90° COD. Therefore, it is clear that a specific recommendation for a representative kinematic description of 'good change of direction' is likely not possible due to the vast combinations of requirements during changes of directions at different angles that occur at multiple velocities in sport.

Additionally, the movement of the athlete during the COD must also be described in context of the requirements of the situation and taken relative to the position the athlete is in at the time of the COD, while also recognizing that more recent research is moving away from the notion of an 'ideal' movement for success (Lee et al., 2014). The kinematics or 'technique' for success in COD can therefore be considered vast and continually changing with respect to the constraints of the physical, perceptual-cognitive and tactical context of COD. These are analogous to the dynamical systems theory application of constraints within physical, mental and social contexts (Latash, 2008). As such, this chapter will focus on COD development through discussions of the task and goal, instead of an overemphasis on technique (Lee et al., 2014), in an effort to reach multiple movement solutions (kinematics) that result in successful COD.

More broad recommendations, however, can be summarized across research that may describe COD movements independent of velocity or angle, with the expectation that the chosen movement will occur with respect to muscle strength, mobility and anthropometry and therefore recommended changes must be considered within that context as well. Technical guidelines have previously been summarized across the areas of visual focus, body positions through deceleration and acceleration, leg action and arm action (DeWeese and Nimphius, 2016). These include use of the trunk during lateral movement (Sasaki et al., 2011) or when there is greater deceleration demands and subsequent increased change in body momentum (Havens and Sigward, 2015a, Havens and Sigward, 2015b), the orientation of the hips toward the direction of travel (Havens and Sigward,

2015a), and good joint alignment of the hip, knee and ankle (DeWeese and Nimphius, 2016) with consideration that some actions, such as increased trunk lean, hip abduction and hip internal rotation, may be necessary for successful completion of more aggressive COD (Havens and Sigward, 2015a). Some of these requirements are often seemingly contrary to suggestions of reducing frontal and transverse movements in an effort to minimize knee adductor moments (Dempsey et al., 2007). However, one must consider successful movement requires loading, and increased capacity and minimization of extremes within these movements are likely more applicable than recommended avoidance to ensure the COD can be successful in the reality of a sporting context.

In conclusion, the joint positions and joint moments that are advantageous for performance are only beneficial if the capacity of the athlete is high enough to tolerate those joint moments without subsequent failure or injury occurring in conjunction with successful performance. Further, the description of the ground contact times required at various angles and velocities vary in magnitude but still contain defined ranges which individuals can use to determine subsequent training requirements. The ground reaction forces (magnitude and direction) required for effective change of momentum during a COD may be produced using multiple joint configurations that are constantly changing due to the physical, perceptual-cognitive and tactical considerations that must be considered.

UNDERPINNING FACTORS RELATED TO CHANGE OF DIRECTION

Inherent to the performance of an effective and efficient COD is having the underpinning physical capacities to perform the technical requirements of the COD. As has been highlighted in the introduction of this chapter, each COD has unique characteristics, and therefore will require varying levels of the different physical capacities. Several models of agility have been proposed (Young et al., 2002, Nimphius, 2014), but each result in different requirements and therefore demand a different approach to physical development. Therefore, the current chapter uses a different approach whereby considerations for the types of COD as the overarching commonality are split into different purposes (see definitions). With such an

approach, it is also acknowledged that when these performances occur in response to situation or opponent, there are several perceptual-cognitive factors that can interact with the perceptual-motor response and subsequent successful or unsuccessful execution of the COD. It is the ability of the athlete to absorb force (braking) and produce force (acceleration) while controlling the body position between and during these phases of movement that are critical in a COD typically performed for evasion. Factors already considered critical for speed are most applicable when a COD is intended to maintain velocity and unique movement, and ability demands influence change of direction into a new mode of travel such as a shuffle, both termed maneuverability in this chapter. If the strength capacity of the athlete is effectively utilized and coordinated within the constraints of the activity, then success is more likely. Such delineation could be described as the difference between ability and skill. Therefore, the next section will focus on the abilities, termed physical capacities, that are important to further enhance skill development of the COD. The subsequent section will then discuss the current understanding of perceptual-cognitive underpinnings of agility.

Physical capacities underpinning change of direction

While maximal strength has been commonly associated with many aspects of sport performance including sprinting and CODS (Suchomel et al., 2016), it should be recognized that the force applied during a COD occurs over a range of ground contact times (see Table 17.1) and over different phases: braking and propulsion. Therefore, the length of time available and characteristics of the COD (see Table 17.1) lend itself to be more associated with eccentric, isometric or concentric strength and relative to the time available (Nimphius, 2014) than just one measure of strength (e.g., a typical one-repetition dynamic performance). Although it is clear that dynamic strength is largely correlated to the specific sub-component measures of strength – isometric, concentric and eccentric (Spiteri et al., 2014b) – the relationship is not perfect, and therefore indicates these sub-qualities of strength can develop at different rates or magnitudes. As highlighted, the required contribution of each sub-quality of strength varies depending on the type of COD required and current physical capacities of the athlete (Spiteri et al., 2015a).

Rate of force development, reactive strength or fast and slow stretch-shortening cycle (SSC) activities (including drop jumps, countermovement jumps and loaded jumps) are also important physical capacities for enhancement of the multi-factorial physical attributes that underpin COD. The reason for an emphasis early in the chapter on ground contact time is to highlight that a COD, where the ground contact time is very short, is likely to be more related to capacities related to fast SSC activities, whereas those with longer ground contacts will benefit from improved longer SSC activities. For example, in shallow cuts or those in response to stimulus where a sudden foot-ground interaction may occur, drop jump performance or reactive strength would be considered relevant to performance, particularly as the increased eccentric phase muscle activity during a drop jump (McBride et al., 2008) could be paralleled to the pre-activity of shallow angle cut agility tasks (Spiteri et al., 2015b). On the other hand, when there is a greater angle of COD, either for evasion or required due to angle, the braking involved results in a longer ground contact, and is therefore likely to be more related to maximal strength (Suchomel et al., 2016), specifically eccentric strength (Jones et al., 2009), and can be improved using higher load, longer SSC activities (McBride et al., 2002).

It is acknowledged, however, that having these physical attributes do not guarantee enhanced COD performance, hence why the association between strength and COD performance often only explains a portion of variance, or can change as an athlete develops (Nimphius et al., 2010). Further, one must also learn to utilize increases in strength within the context of the activity (Suchomel et al., 2016), therefore, consideration should be made for the expected delay or *lag time* between increased physical capacity and ability to actualize the improvement in performance (Stone et al., 2003, Nimphius, 2010). In conclusion, there are several interacting physical capacities and inherent anthropometric characteristics that combine during a successful COD, and the underpinning capacities required are dependent on the type of COD being performed.

Perceptual-cognitive factors underpinning agility

Although a motor response must occur during all COD, most agility manoeuvres are typified by the description of a rapid stimulus-response scenario, and such a scenario is typical of a majority of tests designed to

assess agility (Paul et al., 2016). The decisions that occur in response to a defensive shift, open space or one-on-one scenario in sport require individuals to combine perceptual-cognitive factors (visual scanning, anticipation, pattern recognition, knowledge of situation, reaction time) with a motor response, which in combination can be termed perceptual-motor ability. As such, perceptual-cognitive skill is a function of perception and understanding, while ultimately what one is able to perceive and do with action is what allows for successful execution (Starkes et al., 2004). This circling requirement back to motor response is why the process for understanding and developing COD and agility has started with the motor or physical capacities to ensure a base is present to build from. Such a concept is supported by research demonstrating that although one may make a correct decision (perpetual-motor decision), if they are less skilled they may fail to execute this decision despite making the correct one in the context of the situation (Bruce et al., 2012).

Although all of the described perceptual-cognitive factors can be justified as critical to agility performance, current agility tests only allow limited use of the knowledge of situation, visual scanning and pattern recognition, and therefore are likely more confined to understanding one-on-one scenarios. Skills sessions using open-ended games, varying playing space and active defenders (Farrow and Robertson, 2016) will likely provide a better environment to improve visual scanning, anticipation, pattern recognition and situational knowledge, including evaluating the execution of the perceptual-motor response. This is because the likelihood of their transfer to the game would be considered environmentally and tactically specific. Direct one-on-one scenario training may benefit from targeted training surrounding identifying movement cues to predict movement (Serpell et al., 2011). However, future developments attempting to improve the underpinning processing speed (visual information processing speed and multifocal attention skills) separate to the perceptual-motor response or execution may have promise, but have only been recently evaluated in a few sports (Mangine et al., 2014, Romeas et al., 2016).

SCIENTIFIC RESEARCH AND CURRENT APPLIED PRACTICE

The previous sections that have provided a basis of understanding about the biomechanics of changing direction and the physical and perceptual-cognitive factors that underpin one's ability to produce the kinetics and display the kinematics associated with superior COD are limited to the findings of research to date. There are strengths and weaknesses of the methodological approaches taken thus far that leave much more to be discovered and understood. As a scientist and practitioner, understanding these limitations and placing them into context will allow you to make informed practice decisions. For example, the validity of many of our CODS and agility measurements have been called into question due to many of these tests being focused upon a metric of 'total time to complete' as they measure one's COD ability (Nimphius et al., 2017, Nimphius et al., 2016b, Sayers, 2015).

Although a single measure of COD performance does not exist due to the overarching fact that COD performance is angle dependent (Buchheit et al., 2012, Hader et al., 2015) and velocity dependent (Vanrenterghem et al., 2012), a measure more relevant to the purpose of the COD being performed could be evaluated. For example, the evaluation of COD performance must consider the entry velocity of the athletes into the COD and exit velocity out of the COD (Spiteri et al., 2013), in addition to the time taken to actually change direction (ground contact time of plant phase), the direction of the velocity change for evasion and potentially even the momentum during the COD (Nimphius et al., 2017). All these provide more information than the typical 'total time' measure.

A valid measure of COD and agility based on their definitions should accurately assess the change in direction, velocity or mode, and, as suggested by Sheppard and Young (2006), should represent a distinct physical quality. Despite this understanding, as previously noted, research has primarly used 'total time' without consideration of the large to very large correlations with straight-line running speed observed in the research (Gabbett et al., 2008, Nimphius et al., 2013, Nimphius et al., 2010). Although there are many other limitations that could be discussed about current research into COD ability, the potential to improve on the meaure that best represents this quality may well be the most outstanding limitation to consider. There is some research that has taken a potentially more valid approach to evaluating COD ability by assessing an individual's center of

mass during a COD (Wheeler and Sayers, 2010, Sayers, 2015, Hader et al., 2015, Spiteri and Nimphius, 2013).

It is therefore possible that future research using this more direct measure of how well a person changes direction may change or at least advance our current knowledge on the topic. The primary reason for such a conclusion is that it has been demonstrated that the chosen measure of COD performance can influence the conclusion made. Specifically, previous research conclusions have shown to be altered depending on the metric used as the ‘measure of COD ability’. For example, Nimphius et al. (2016b) compared the use of a traditional ‘total time’ measure of performance and the COD deficit during the 505 COD test, demonstrating that the metric chosen to evaluate COD changed the perceived COD ability of the athlete in more than 88% of the athletes assessed. More relevant to the comparison of total time to entry or exit velocity were the alternate conclusions that total time was not sensitive enough to detect significant differences in stronger and weaker athletes, while there was a significant difference in exit velocity of strong and weaker athletes (Spiteri and Nimphius, 2013).

These issues hold true with agility testing as well. Further, agility tests still require improvements in ecological validity, as one should acknowledge the current tests mostly focus on one-on-one scenarios, and should consider multiple players, alternative visual perspective and deceptive actions (Paul et al., 2016) to allow for better evaluation of a larger number of the perceptual-cognitive factors (see Figure 17.2) of agility. Gathering all of this information within a practical setting would be complex and time consuming, therefore recommendations will be made with respect to the method of timing or variable to represent performance, choosing a COD test and considerations for agility tests within the context of a typical practitioner in Section 2.

SECTION 2

QUANTITATIVE EVALUATION OF CHANGE OF DIRECTION AND AGILITY PERFORMANCE

There is still more to be understood as more isolated measures become common in both applied and scientific settings when assessing COD ability. The complexity of COD assessment is that a COD is performed for multiple purposes. Therefore the ‘metrics’ may change based on the purpose, hence why there will likely never be a single, ideal measure of COD performance. Practitioners drawing conclusions from research must first determine the purpose of the knowledge they require. Therefore, one should determine if they require knowledge on best evasion ability, ability to maintain velocity, ability to tolerate the most demanding braking requirements or to assess general physical capacity to perform a COD at various angle range(s) before generalizing the results and conclusions. A recent review of the most common CODS and agility tests with information on the length of test, angle of COD and number of COD can be sought in existing literature (Nimphius et al., 2017) and may be useful in addition to abbreviated information in Table 17.2.

To understand how to choose an appropriate COD assessment, one should first compare the common CODS tests or agility tests and classify them into the more specific delineations under the larger umbrella of ‘COD’ that have been defined in this chapter. Therefore, Table 17.2 has been expanded upon from previous examples of classifying different CODS and agility tests (Nimphius, 2014, DeWeese and Nimphius, 2016). One can draw information from this table on whether a test is evaluating multiple attributes, is long in length and therefore may be confounded by anaerobic capacity if being assessed before and after a training block and the angle changes that occur. Such a classification can be performed on any existing or created CODS or agility test.

With an understanding of the current CODS tests and their ‘classification’, or different factors that influence the result, one can begin to improve or select better metrics to identify COD performance. As discussed, one should try to isolate the COD performance intended to measure. A simplified approach to assessing COD performance has recently

been proposed (Nimphius et al., 2016a) where a single COD of various angles are performed over the same distance and then a change of direction deficit can be calculated (Nimphius et al., 2016b, Nimphius et al., 2013). Suggestions to measure the COD performance over shorter distances that surround the actual COD (Sayers, 2015), or the aforementioned COD deficit (Nimphius et al., 2016b), are attempts to practically solve an issue whereby the measure (total time) is not isolating or reflecting the actual performance (COD) intended to be measured. When more equipment is available, it is likely the most accurate method to assess COD performance will be to evaluate the COM of an athlete during the COD as performed using three-dimensional motion analysis (Havens and Sigward, 2015b, Wheeler and Sayers, 2010, Sayers, 2015) or using laser distance meters (Hader et al., 2015). However, these techniques are less readily available than timing gates, hence suggestions of more practical methods of assessing COD performance. An example of an athlete's assessment is provided in Figure 17.2 with a summary of standardized performance (using a z-score) across several physical capacity assessments and different measures of COD that were considered relevant for this athlete. This information will be used in the section 'Programming to improve change of direction and agility' as an exemplar of developing a program using performance results.

TABLE 17.2 Example classification of existing change of direction speed and agility tests

	COD with a 'cutting' movement	*Maneuverability*		*Perceptual-cognitive (test requires response to a stimulus)*	*Metabolic requirement (time to complete test)*	*Total distance*
		To maintain velocity	*Change in mode*			
Common Y- agility tests	~ 45°	*Depends on tactic*	×	✓	~ 1.5–2.5s	~ 8–11m
AFL Agility Test	×	✓	×	×	~ 8–9.5s	~15m
L Run	180°	✓	×	×	~ 7s	~ 27m
Illinois Agility Test	180°	✓	×	×	~ 13–19s	~ 60m
T-test	90°	×	✓	×	~ 7.5–13s	36–56m
Traditional 505	180°	×	×	×	~ 3s	10m

Note: Data and information is modified from (Nimphius et al., 2017)

QUALITATIVE EVALUATION OF CHANGE OF DIRECTION AND AGILITY PERFORMANCE

A majority of evaluation of COD is focused on quantitative measures. However, coaches should consider evaluating the quality of the COD or the strategy of athletes performing a COD in conjunction with the quantitative measures. Of particular importance is a qualitative assessment of athletes returning to play following an injury. Athletes will often find a method to ‘beat or pass a test’ lending them to focus more on the goal than the process, and with athletes returning from injury this process may involve strategies that are avoidant of the previously injured limb. If observed, it can be called into question whether that athlete has successfully proven their ability to withstand the loading during the chosen COD test, or whether they are psychologically confident in the capacity of the previously injured limb, both reasons indicating an athlete may not be ready for a full return to play.

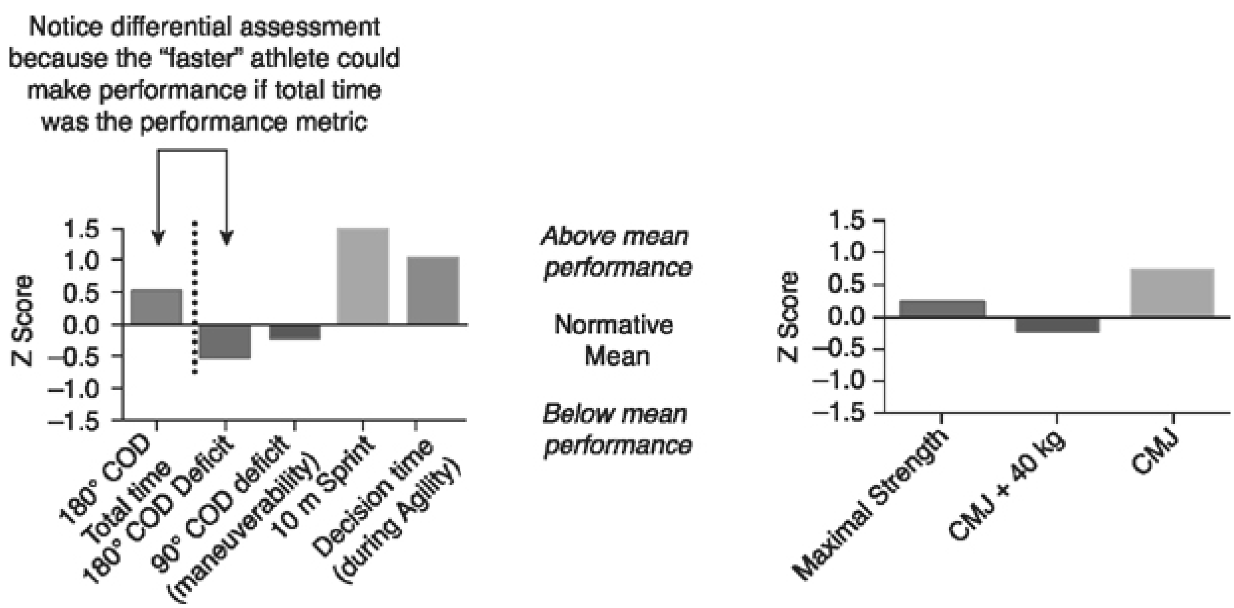

FIGURE 17.2 Example assessment of COD and physical capacity. To demonstrate the difference between total time and COD deficit measures, both assessments have been provided.

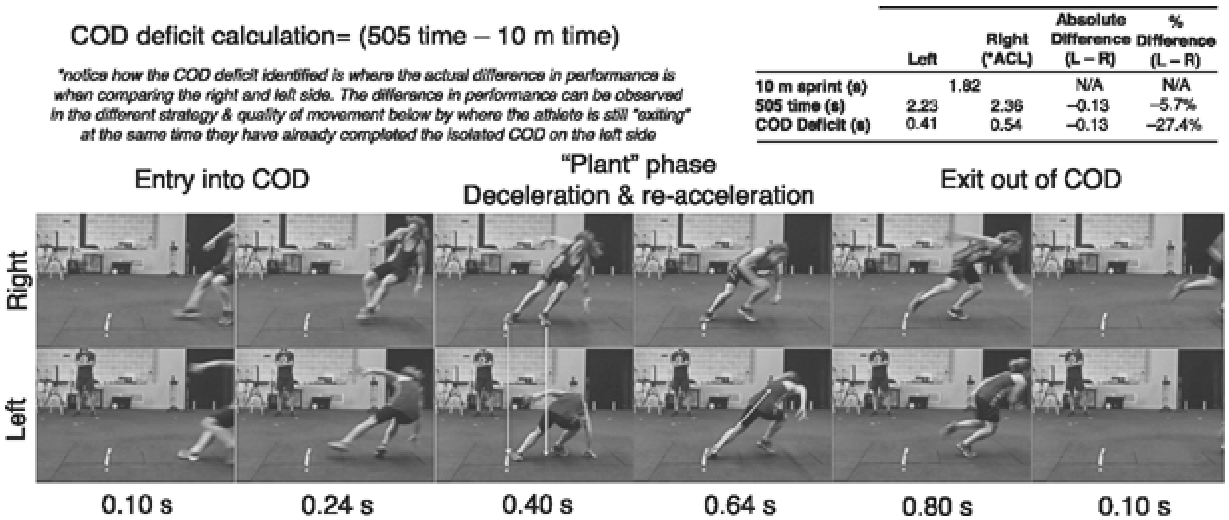

FIGURE 17.3 Qualitative assessment of COD performance during a 180° COD. This figure is modified from the following article, so if required, you may reference (Nimphius et al., 2017).

An example of different observations after return to play can be seen in Figure 17.3 with a comparison of a 180° COD during a traditional 505 on the right and left sides. The right leg of this athlete underwent an ACL reconstruction surgery approximately two years prior to this testing. Performance measures include: total 505 time and COD deficit (505 time – maximal 10m sprint time). Further, the percentage difference between right and left sides is shown in the table. This athlete is well above team mean performance, which may have led a coach to not be overly concerned with assessing technical differences in the COD.

However, with this athlete, technical differences provide vast information beyond the discrete time measures. Notice the differences in the strategy as they preferentially load the left leg while changing direction, the 'right' side has less effective body position as a result of ineffective load absorption (compare position at 0.64s), and the result is a less effective COD as they would still be 'present to be tackled' at 1.10s when turning on the 'right' side. Such a qualitative analysis would lend one to ensure the athlete has adequate capacity building and potentially some task constraints in their drills to ensure she loads and develops strategies for a COD on either side. Athletes can avoid movement strategies in planned scenarios; however, if they present these movement strategies in planned tests they may be at risk in scenarios where they can't use their preferred strategy, which is why some closed drills with tasks and constraints are critical for

athlete development and return to play. This will be discussed in the next section when discussing ‘inside and outside leg loading’ as an example of a closed drill with constraints that still allow for movement solutions to be created, but with more targeted loading strategies from a capacity building and accountability stand point.

CAPACITY BUILDING AND SKILL ENHANCEMENT: A MODEL OF COD DEVELOPMENT

The development of physical capacity should be considered in association with skill development, and different stages of the development process will have a greater emphasis on physical capacity development versus skill development. However, as discussed in Figure 17.4, the emphasis constantly shifts, and development is never considered all physical or all skill as they are intimately linked. It is suggested that coaches should utilize a constraints-led approach (Davids et al., 2008) in an effort to increase the number of movement solutions an athlete is required to have for the same ‘drill’. For example, an athlete performing a ‘back door cut’ can load their inside or outside leg (i.e., plant leg) to a greater degree, however, both scenarios are common in sport (e.g., leading a defender versus reacting as a defender) even though one will likely be the ‘faster’ performance. Exposing the athlete to a range of solutions by setting constraints, e.g., touching a hurdle while concurrently restricting how close they can get to it (forcing them to reach and load the outside leg) allows for several solutions using the same drills (e.g., ‘back door cut’ or 180° turn). As a result, the focus can be on the development of a movement solution instead of ‘learning the drill’.

This ‘repetition without repetition’ is indeed the context of the dynamical systems approach discussed by Bernstein (1967) and highlighted in the proposed model of COD development in Figure 17.4. In addition, the organization of skills practice should be considered within the context of the skill level of the performer and purpose of the phase. It is also important to ensure a shift from block to serial to random practice (Farrow and Robertson, 2016), while also considering the aspects of building capacity versus enhancing skill. Furthermore, it is important to consider the appropriate amount of time to utilize tasks and constraints to increase

contextual interference in an effort to enhance skill learning in COD. This holds true during ‘pre-planned or controlled’ and ‘reactive’ environments (as summarized in Figure 17.4).

Further, actualization of training from improving physical qualities into skilled movement can be affected by the instruction provided by the coach. Within CODS research, it has been shown that externally focused attention, where one provides instruction that focuses attention on the environment, improves timed performance (Porter et al., 2010). However, a greater understanding of the influence of training experience has indicated that in sprinting (as sprint speed is a large part of the CODS tests currently utilized) either a normal focus or external focus was beneficial in comparison to internal focus for moderate level sprinters. However, as experience level increased, the benefit of external versus internal focus declined likely due to their highly developed implicit motor plans (Winkelman et al., 2017). Therefore, when considering the daily training environment for COD development, coaches should consider the purpose of the session followed by choosing the best practice environment (e.g., blocked versus random), level of contextual interference and the type of feedback or instruction that is most appropriate to achieve the purpose relative to the expertise of the group being trained.

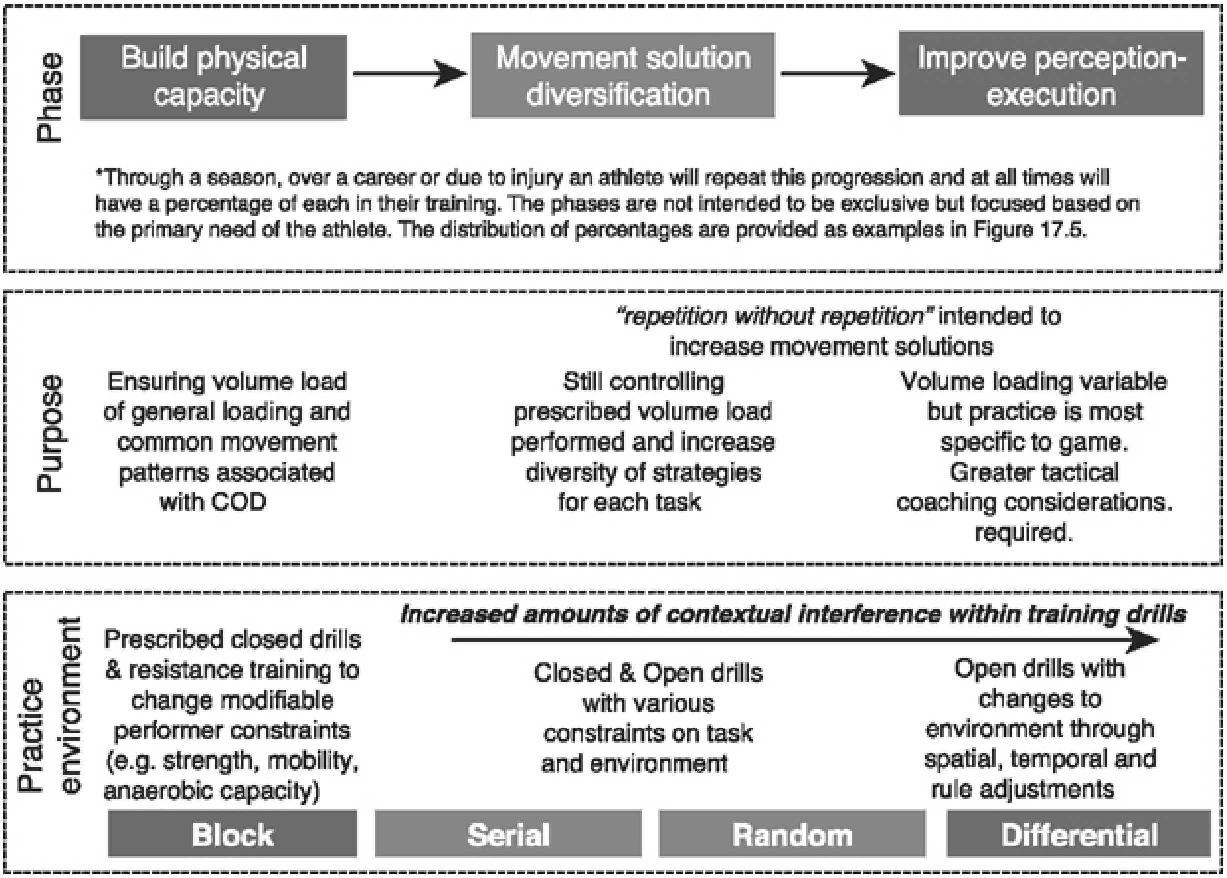

FIGURE 17.4 Proposed change of direction development model.

PROGRAMMING TO IMPROVE CHANGE OF DIRECTION AND AGILITY

As was originally presented in Figure 17.2, the assessment of an athlete can determine the focus of the subsequent training blocks that will follow the conceptual model of Figure 17.4. By assessing the athlete appropriately, one can ensure the training is targeting an area that requires improvement. A needs analysis should be performed for the sport of the athlete followed by the strength and weakness assessment. Next, one will usually identify a primary and secondary need of the athlete and then create a plan by distributing the time available based on need. For this example, we will proceed with the information provided as per Figure 17.5. This plan outlines the strengths and weakness of the athlete based upon the data in Figure 17.2, and then identifies the primary and secondary emphasis with a proposed time distribution focus for the current block and how this may

change over the subsequent blocks as the athlete develops. Further, an example single session is provided to demonstrate how to use the COD development model to determine not only the long-term but also the daily training process.

SUMMARY

To effectively develop and enhance COD ability, it is critical to accurately identify the strengths and weaknesses underpinning COD performance in combination with understanding how well the athlete utilizes their physical attributes within the context of the skilled performance of changing direction. A mixed method qualitative and quantitative approach to evaluation followed by a progressive development that aims to enhance the transfer of underpinning physical attributes to their use in the technically demanding aspects of changing direction is recommended. Through effective planning and use of both capacity building and skill development processes, an athlete can improve this often underdeveloped and misunderstood athletic quality.

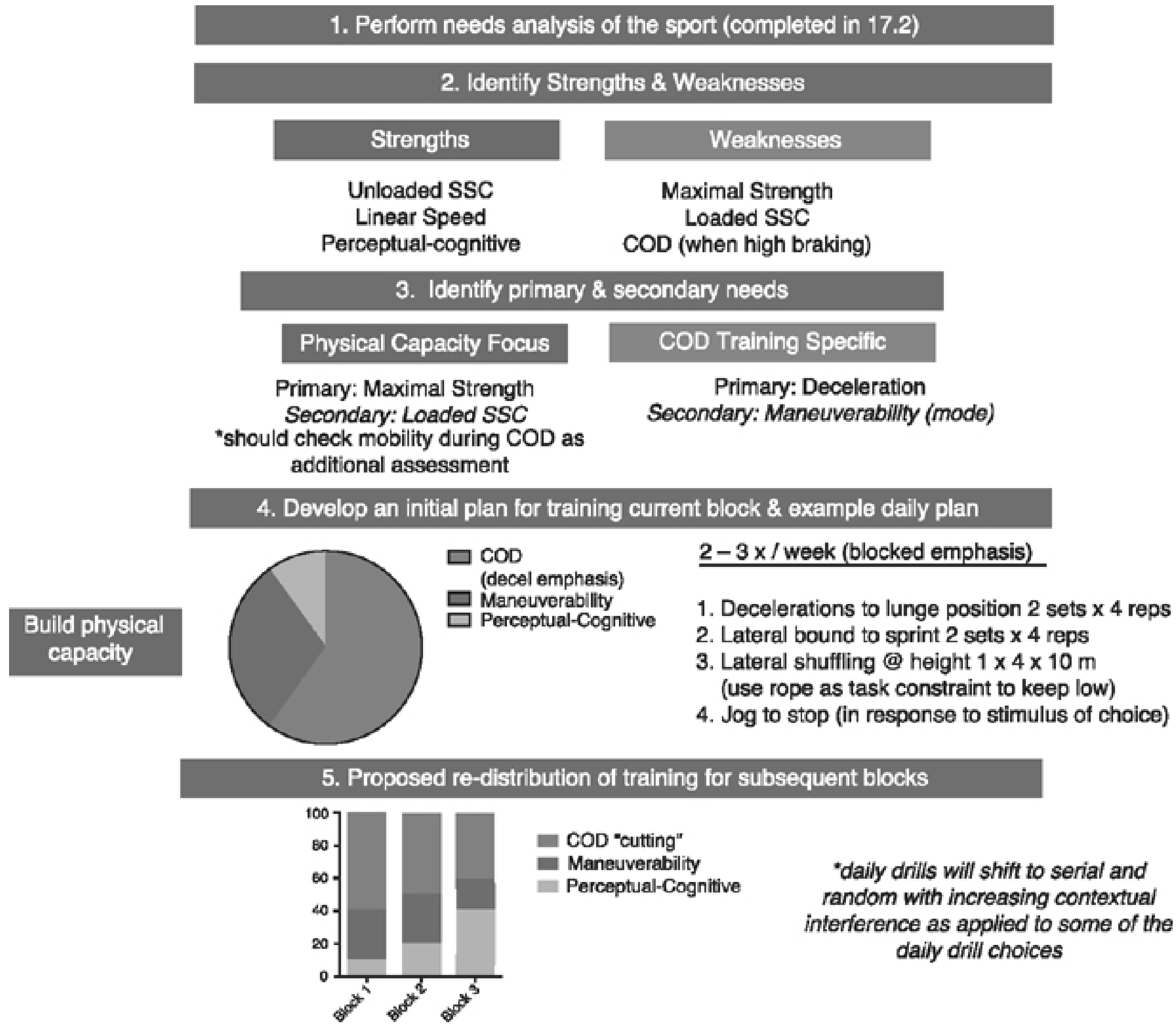

FIGURE 17.5 Example program from needs analysis through to long-term planning for subsequent blocks of training.

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CHAPTER 18

Speed and acceleration training

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SPRINT

Sprint running is considered the fastest mode of human locomotion (Nagahara, Matsubayashi, Matsuo, & Zushi, 2014a). The analysis of sprinting is relevant to a better understanding of the muscles and forces generating the highest levels of performance. Sprint running, and more specifically sprint acceleration, is a key component and is central to performance in many sports including football, soccer, and rugby (Cronin & Sleivert, 2005). Sprint, power output, and forward acceleration are key physical determinants of successful athletic performance and are essential components of strength and conditioning training programs in many sports and recreational physical activities.

Although maximal straight-line single-bout speed is the focus of many track events, and sprint running speed is also considered a relevant parameter for field-based team-sports (Simperingham, Cronin, & Ross, 2016), it is important to emphasize that the ability to accelerate over short distances should be prioritized in many sport activities rather than maximal velocity, since maximal velocity is rarely achieved in these kinds of sports (Morin, Slawinski, et al., 2015; Spencer, Bishop, Dawson, & Goodman, 2005). Sprinting in field-based team-sports can vary from short (e.g., Futsal, Rugby union forwards) (Deutsch, Kearney, & Rehrer, 2007) to long (e.g., Australian rules football) (Veale, Pearce, & Carlson, 2007) distances.

Acceleration is a key factor in field-based team sports since players who accelerate more rapidly have an advantage due to the frequent occurrence of such accelerations (e.g., 5–20m, 2–3 seconds) during games (Schimpchen, Skorski, Nopp, & Meyer, 2016; Spencer et al., 2005). Recent studies suggest that 68% of sprints in rugby (Gabbett, 2012) and 90% of sprints in soccer (Vigne, Gaudino, Rogowski, Alloatti, & Hautier, 2010) are shorter than 20m, and this is not enough distance for players to reach maximum velocity. In addition, such short linear sprints are used in decisive actions (Faude, Koch, & Meyer, 2012).

Several factors influence acceleration performance, including the magnitude of the applied force and the ability to apply the force effectively in the forward direction (Morin, Edouard, & Samozino, 2011; Morin et al., 2012). From the simple laws of dynamics, the acceleration of a body in the forward direction is proportional to the amount of ground reaction force produced in that direction. This has been experimentally confirmed in many types of athletes, ranging from non-specialists to world-class sprinters (Morin et al., 2011; Morin, Gimenez, et al., 2015; Morin, Slawinski, et al., 2015; Morin et al., 2012; Rabita et al., 2015). Furthermore, in recent years, a new insight into sprint acceleration mechanics has been proposed which considers the mechanical ability to produce horizontal external force during sprinting through the athlete’s Force-velocity (F-v) profile (Morin & Samozino, 2016; Samozino et al., 2016). Recent studies (Morin et al., 2011; Morin, Slawinski, et al., 2015; Rabita et al., 2015) have shown that the main mechanical determinants of sprint performance are the absolute physical ability (maximal force and power attributes) of the athlete, and the technical ability to optimally handle this physical ability and apply the ground reaction force effectively (i.e., with a more horizontally-oriented angle).

To date, research in this area is lacking, and most studies have focused primarily on different training methodologies (Rumpf, Lockie, Cronin, & Jalilvand, 2016), kinetics, kinematics, ground reaction forces, stiffness, electromyographic (EMG) activity patterns, and transfer of heavy-weight strength training to sprint performance (e.g., Rumpf et al., 2016; Seitz, Reyes, Tran, de Villarreal, & Haff, 2014). However, research is ongoing to determine which training modalities and exercises may be used in the field to improve horizontal force and associated sprint acceleration performance, including resisted and assisted sprinting as well as specific exercises for improving technical ability during sprinting.

To enhance performance in athletes requiring high levels of acceleration, it is crucial to understand the mechanical underpinnings of sprint acceleration, and athletes' subsequent training based on F-v profiling. In this chapter, we will discuss some of our current work in this area, and use the descriptive model "generate force and transmit it to the ground" to describe exercise modalities that may improve the various components of this model and answer the question: "Which exercises may contribute to improving force production, and which exercises may improve mechanical effectiveness and force transmission ability?"

Sprint: General description

Typical sprint-track running is characterized by a velocity time-curve and can be divided into three phases; acceleration, constant velocity, and deceleration (Mero, Komi, & Gregor, 1992). In recent years, sprint running has also been divided into three phases described as early acceleration, acceleration, and maximal velocity. During these phases, sprint technique is modified. However, two phases are present during the whole sprint cycle: the stance phase (support phase) and the flight phase (swing phase). Maximum speed is relevant in track events and limited field-based team sport contexts, such as Australian rules football (Veale et al., 2007). Whereas acceleration of specific parameters is of relatively greater importance when covering only short distances at maximal effort, as is common in many field-based team sports (Simperingham et al., 2016). For instance, in team sports, first step quickness has been considered an important parameter for acceleration; this is defined as the first 0–5 meters and is included in the acceleration phase and characterized by a high propulsion force (Sleivert & Taingahue, 2004). Traditionally, several factors/parameters have been investigated concerning acceleration and sprint performance, providing the basis for understanding the ability to run fast. Some of these parameters are: stride length and frequency; ground contact time and flight time; joint torques and joint angle movements; ground reaction forces; stiffness; and EMG activity patterns. Classically, it was considered that if an athlete simply moved their lower limbs faster, thereby increasing the step frequency, they would reach higher levels of acceleration and maximum speed. Weyand et al. (2000) were among the first to debate this notion, concluding that it is the force production

capability of the body, resulting in greater ground reaction forces (GRFs), that is the strongest determinant of maximal running speed in humans. There is a large body of literature supporting this statement (e.g., Clark & Weyand, 2014; Weyand, Sternlight, Bellizzi, & Wright, 2000; Weyand, Sandell, Prime, & Bundle, 2010). Although in recent years, research by Morin and colleagues (Morin et al., 2011; Morin, Samozino, Bonnefoy, Edouard, & Belli, 2010; Morin, Slawinski, et al., 2015; Morin et al., 2012) highlighted the forward orientation of GRFs as a further determining factor of performance, specifically in the acceleration phase of the sprint, and observed that the vertical component of the GRF was not related to performance in that phase. Thus, some contrasting results can be found, and it seems that examining sprint running mechanics and force production in more depth is important to understanding and improving sprinting performance both in track events and field-based team sports.

The acceleration of an athlete’s center of mass during sprint running is determined by body mass and three external forces acting on the body: (a) ground reaction force (GRF); (b) gravitational force; and (c) air or wind resistance (Samozino et al., 2016). GRF can be divided into three components (antero-posterior, vertical, and medio-lateral) although typically the antero-posterior (horizontal) and vertical components are the most studied and most relevant for sprint performance (Hunter, Marshall, & McNair, 2005; Morin et al., 2011; Rabita et al., 2015). The horizontal orientation of applied force should be considered when studying GRF during the support phase since the ability to produce and transfer greater forces may allow for shorter ground contact times and a shorter braking phase during contact, which could support the importance of the hip extensors and the ankle stabilizer muscles in training.

Classically, running speed has been described as the product of stride rate or frequency and stride length, assuming that to increase velocity it is necessary to increase at least one, if not both (Hunter, Marshall, & McNair, 2004; Weyand et al., 2000). Typically, maximum stride frequency is reached between 10m and 20m, and at this point, stride length is about 75% of the maximum value reached during the maximum velocity phase. During the acceleration phase of a sprint, greater increases in horizontal propulsion are required to achieve high acceleration (Hunter, Marshall, & McNair, 2005; Morin et al., 2011).

Ground-leg interaction is the major determinant in sprint running since it is during the contact or support phase of the step cycle that segmental forces can act on and in turn influence horizontal speed. Running is characterized by support (the foot is in contact with the ground) and swing phases (the time between when the lead foot leaves the ground and when it next makes contact with the ground). During the stance (support) phase, the athlete absorbs braking and vertical forces and then produces propulsive force to displace the body forward, while during the swing phase the athlete repositions the limbs in order to prepare for the next stance phase. Forward acceleration is key in sprint running. A typical support phase can be divided into a braking phase (backward orientation of the horizontal force vector; negative horizontal GRF) followed by a propulsive phase (positive horizontal GRF) (e.g., Hunter et al., 2005; Morin et al., 2011; Morin, Slawinski, et al., 2015; Rabita et al., 2015).

Mechanical determinants of sprint and acceleration performance: produce force and transmit it to the ground

The aim of this section is to present evidence from existing scientific data to provide a better understanding of the underpinnings of the muscular determinants of sprint acceleration performance supporting our model of "produce the force and transmit it to the ground" and the technical ability to apply force, which will provide the basis of practical training methods to optimize sprint acceleration performance.

Muscular determinants of sprint and acceleration in performance

Sprint performance implies large forward acceleration, which is directly dependent on the ability to develop and apply high levels of horizontal external force into the ground at various speeds over the sprint acceleration period (Morin et al., 2011). This is why the ability to produce GRF with a magnitude and timing unique to each individual phase of the sprint becomes paramount, changing from a high force at low speed in the early acceleration phase to low force at high speed in the maximum speed phase (Morin et al., 2012). Muscle roles shift within the distinct acceleration

phases, suggesting that a better understanding of "what force is happening at what speed" is very important in order to design specific training methods and therefore enhance muscle function during forward propulsion.

The most widely studied muscles in sprinting are the hip extensors (hamstrings and gluteus maximus), knee extensors (quadriceps), and plantar flexors (soleus and gastrocnemius). It is widely accepted that most muscles activate at the highest levels just before or at the beginning of ground contact (Morin, Gimenez, et al., 2015). It is mainly during this support phase—the single instant when force can be applied to the ground—that the muscles responsible for hip, knee, and ankle movements play a specific role in acceleration performance, efficiently propelling the body forward.

When analysing sprint acceleration from a purely biomechanical perspective, great differences/contrasts can be observed among the three phases previously described. These differences provide critical information for a better understanding of the underlying parameters responsible for this differentiation when talking about muscles' roles or patterns of action. These variations become more evident during the very early steps, when body-positioning force is applied. This phase is characterized by a greater forward lean of the trunk (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013; Nagahara et al., 2014a and 2014b) and a longer time for the application of force of approximately 190ms versus ±101–108ms when the maximum velocity phase is reached (Wild, Bezodis, Blagrove, & Bezodis, 2011; Yu et al., 2016).

In this first stage, the hip and knee extensors work alongside the soleus and gastrocnemius to achieve a triple joint extension of the lower limb and provide forward propulsion to the body mass. Although during this first ground contact time (GCT) the relative net horizontal impulse is greater than the vertical one (Kawamori, Nosaka, & Newton, 2013), both the calves and the quadriceps significantly contribute to forward displacement of the center of mass, together with the main muscle groups responsible for this function throughout the entire race: the hip extensors (Morin, Gimenez, et al., 2015; Schache, Brown, & Pandy, 2015). This is possible since the more inclined and gathered position prevailing in this phase enables the involvement of muscles that normally produce vertical force during concentric contraction—the quadriceps, soleus, and gastrocnemius—acting here to provide horizontal propulsion because the resulting vector of the applied force in this case is mainly diagonal, not vertical (Kugler &

Janshen, 2010). The other major difference lies in ground contact patterns. Firstly, the time available to produce this force varies since the impulse required to overcome the body's inertia mainly depends on the displacement velocity when body mass is fixed. The second factor is the distribution of propulsive and braking roles during each different phase (Morin, Slawinski, et al., 2015). During acceleration, most of the time in the ground contact phase is spent applying propulsive GRF (approximately 87–95% of total GCT) (Hunter et al., 2005; Sleivert & Taingahue, 2004), which is paramount to sprinting success. Therefore, this phase may be mechanically characterized by an involvement of the knee and hip extensors, in addition to the calves, to provide propulsion during the stance phase, which is distinguished by large contact times enabling the development and application of high levels of force into the ground, also made possible by the low displacement velocities.

The second phase is still included within the acceleration phase; however, from a kinematic point of view this second phase is mostly characterized by a gradual decrease in the body's forward lean (Nagahara et al., 2014a and 2014b), the achievement of maximal stride frequency, and a marked increase in stride length with a continuous rise in running velocity (Nagahara, Naito, Morin, & Zushi, 2014b). This higher speed is also associated with shorter ground contact time and important consequences on the kinetic patterns. When considering muscle involvement levels during accelerated running, forward propulsion predominantly depends on the hip extensors—i.e., concentric action of the gluteus and eccentric action of the hamstrings (Morin, Gimenez, et al., 2015)—while the knee extensors and calves progressively adopt a more focused role in the stabilization and transmission of forces as the speed of movement is increased (Mann, Moran, & Dougherty, 1986; Schache et al., 2015). It is for this reason that during this second phase the force is applied in a different way, requiring smaller forces than during the first steps, but applied at a considerably greater speed. In turn, this reduction in available time for developing and applying force into the ground is probably associated with the importance of explosiveness (rate of force development) and the effectiveness of ground force application.

During the maximum speed phase, the plantar flexors (gastrocnemius, soleus) in conjunction with the dorsiflexor (tibialis anterior) muscles have a major influence on how effectively the forces of different body segments

are transferred to the ground. In fact, the gastrocnemius-soleus-achilles complex (GSAC) has been shown to play a relevant role in horizontal propulsion during the contact phase by storing and releasing elastic energy to aid the body's forward projection. A review of the current literature indicates that a change of pattern is observed, since this still-significant contribution is mostly explained not by a concentric action of the GSAC but by an eccentric action. In turn, as for the GSAC, knee extensor activity is modified throughout this last phase, changing from power generation to a function more focused on the absorption and transmission of power (Schache et al., 2015). These changes can be interpreted mainly in terms of the differences observed in the kinetics of the body segments, where a remarkable modification of the knee and ankle angles—which are notably greater when compared to the first phase—can be observed at the moment of touchdown (Nagahara et al., 2014a and 2014b). This action, together with a significant reduction in ground contact time caused by considerably higher speeds, implies a limitation of mechanical ability during force application/development given the short period of time. All these observations point to the hip extensors as the major muscles responsible for forward propulsion during every phase of acceleration (Morin, Gimenez, et al., 2015). Thus, as suggested by Morin et al. (2015), it is important from a practical standpoint to reinforce hip extensor strength and knee flexion strength (including the eccentric action mode) to improve sprint acceleration performance.

The evidence thus points first to the possibility that the muscular strategy chosen for the generation and transmission of forces during the acceleration phase is shifted as running speed increases. These modifications seem to be due to the mechanical differences present in every phase, which display characteristic kinetic and kinematic features. It seems likely that regardless of the observed phase, sprinting ability follows a sequential kinetic linking pattern, displaying an energy flow in a proximal-to-distal sequence. From this perspective, the muscles play two distinct roles: producing force and transmitting it into the ground.

Effectiveness of force application onto the ground

Accelerated runs are typically characterized by a support phase, which is mainly defined by a negative horizontal ground reaction force (GRF)—a

braking phase—followed by a positive horizontal GRF in the propulsive phase (e.g., Hunter et al., 2004). Considering the possible decomposition of the forces exerted into the ground, only the horizontal component of the GRF will influence the forward displacement of the center of mass of an athlete (Brughelli, Cronin, & Chaouachi, 2011; Morin et al., 2011), while the vertical and medio-lateral components will play a less significant role during acceleration.

Given the gravitational constraints present during an acceleration run, most of the total (resultant) GRF is produced in a direction that is not characteristic of the athlete's displacement. This vertical force (VF) is not directly linked/related to modification of the displacement speed. Even when an increase in velocity occurs, a stabilization in VF production appears when 60% of the maximum speed is reached (Brughelli et al., 2011), however, horizontal forces increase linearly with increasing speed.

The evidence points to the fact that during acceleration, only the horizontal component of the total force induces body mass forward displacement, meaning the other component (vertical) is ineffective in producing forward acceleration, although necessary to keep moving forward (Morin et al., 2011). Once top speed is reached, the importance of the vertical component is greater (Clark & Weyand, 2014; Weyand et al., 2000; Weyand et al., 2010).

In order to express the relative distribution of horizontal force (HF) compared to the resultant GRF, the ratio of forces (RF) is defined as the percentage of HF to the corresponding total GRF averaged over the support phase (FTot). This is used as an appropriate index to objectively calculate the effective force applied into the ground in order to analyse the technical efficiency during the support phase.

This novel and simple index explains much of the mechanics underpinning acceleration performance, adding kinetics to the conventional spatio-temporal analysis. This perspective provides evidence that despite the development of similar GRF levels in homogeneous groups of athletes, factors related to technical ability are able to alter the RF and give rise to different sprint acceleration performances. Indeed, researchers (Kawamori et al., 2013; Kugler & Janshen, 2010; Morin et al., 2011; Morin et al., 2012; Rabita et al., 2015; Slawinski et al., 2017) have observed that when subjects were compared within the same level group, those who performed better in the acceleration run (and on the overall 100m distance) did so on account of

a better orientation of the GRF and not because of a greater total amount of GRF.

The emergence of this new analysis of the kinetics of the sprint was accompanied by confirmation of the hypothesis that had argued that the ratio of forces present in each of the phases (and practically at each step) varies, showing a greater horizontal component (and therefore a higher RF) during the first support phase. These data confirmed what seemed obvious; the stage where a greater index of horizontality in the application of forces (RFmax) occurs is located during the very first steps. Conditions such as the arrangement of the body segments and the very low or null velocities of displacement existing during these early stages of acceleration enable the generation of large horizontal forces necessary for starting forward propulsion. As these velocities increase, RF decreases as a consequence of the inability to maintain acceleration levels and change both at the kinetic level (i.e., shorter contact time) and the kinematic level (i.e., a more erect body position that favours the transmission of forces rather than the generation of them).

To describe this systematic decrease in RF with increasing speed, the same authors developed an index of force application technique (DRF). Basically, those athletes able to maintain their ability to produce horizontal force (and thus further produce net horizontal force while accelerating) despite the increasing velocity will produce a higher DRF value (i.e., a flat RF–speed relationship), while those whose RF decreases to a greater extent as a result of this increase in speed will have lower DRF values (i.e., a steeper RF–speed relationship) (see Figure 18.1). Typically, non-sprinters have a DRF of about –10% whereas the best sprinters have DRF values of –4 to –6% (Morin et al., 2012; Rabita et al., 2015).

In addition, athletes who exhibit better DRF values (which should be considered as a “technical” parameter since it is not correlated to the amount of force applied, i.e., “physical capability”) are better performers in sports where maximum speed is a priority, such as the 100m sprint, since they are able to still produce net horizontal force, and thus orient and transmit horizontal forces while their speed of movement is increasing.

FORCE-VELOCITY PROFILE DEFINITION AND FIELD COMPUTATION METHOD

Sprint running implies large forward acceleration and is related to the capacity to produce and apply high power outputs in the horizontal direction into the ground (i.e., high horizontal external forces at various velocities during sprint acceleration). The overall ability to produce horizontal external force during sprint running is well described by the inverse linear F-v and parabolic power-velocity (P-v) relationships (Jaskólska, Goossens, Veenstra, Jaskólski, & Skinner, 1999; Morin et al., 2011; Morin et al., 2010; Rabita et al., 2015) through which maximal power output may be improved by increasing the ability to generate force output at low levels of velocity (a force-dominant profile), maximizing velocity production at low levels of force (a velocity-dominant profile), or both (Morin et al., 2016). The assessment of horizontal power and mechanical relationships during sprint running is essential to understand the specific determinants of sprinting performance. Since horizontal power and its associated determinants are highly related to acceleration ability during sprint running (Morin, Gimenez, et al., 2015; Rabita et al., 2015), researchers have attempted to develop methods to assess these sport-specific determinants accurately to gain a better understanding of running performance. In recent years, the inclusion of F-v relationships and their contribution to ballistic performance has provided a more accurate and integrative mechanical representation of the athlete's maximal capabilities (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012), encompassing the entire force-velocity spectrum, from the theoretical maximal force (F0) to the theoretical velocity (v0) capabilities (Morin & Samozino, 2016).

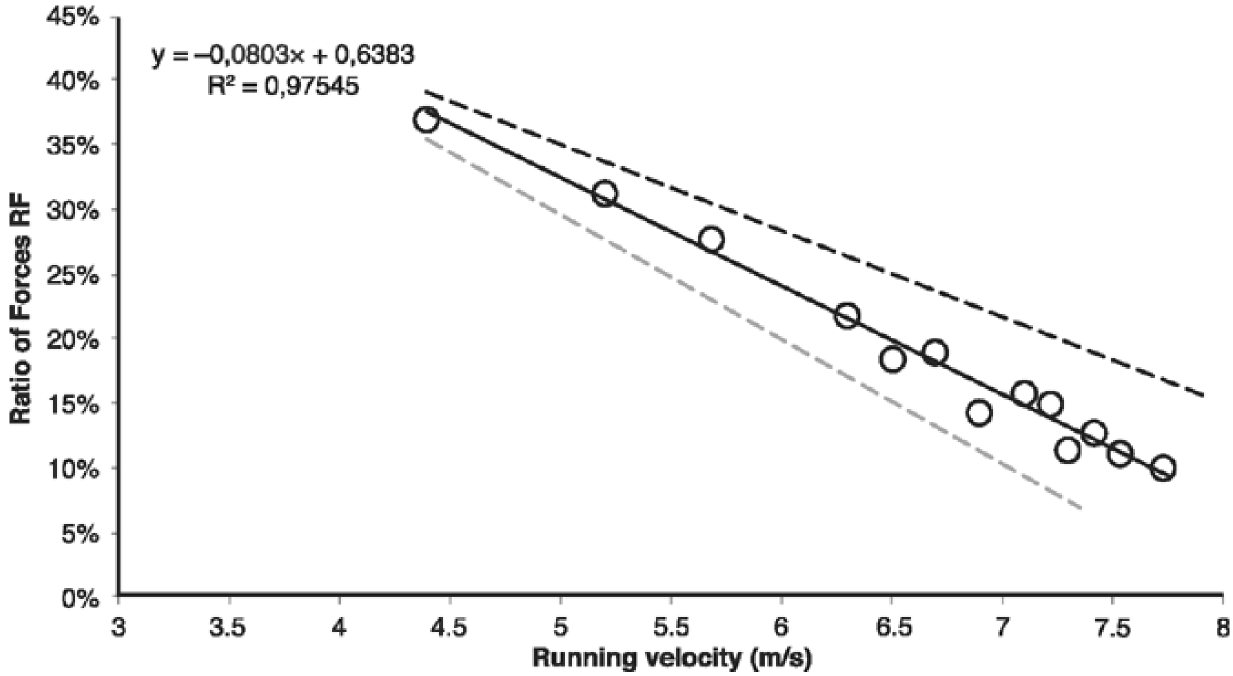

FIGURE 18.1 Ratio of forces (RF) and index of force orientation (DRF). Typical example of the RF-speed linear relationship obtained during a six second sprint on an instrumented sprint treadmill. Each point corresponds to values of RF and running speed averaged for one contact phase. The DRF index value for this subject is –0.0803. The dashed lines would correspond to a better index for the black line (flatter relationship, i.e., more horizontal force produced as speed increases) and a worse index for the grey line (steeper relationship, i.e., the horizontal force drops faster as speed increases).

Since these mechanical features could previously only be measured during sprints on an instrumented treadmill (Morin et al., 2010; Morin et al., 2012) or on track-embedded force plate systems (Rabita et al., 2015), a simpler method has been proposed and validated. This method requires simple distance- or velocity-time data to model external horizontal force measures and associated F-v and P-v relationships during the entire acceleration phase of an over-ground sprint (Samozino et al., 2016). This method uses a computation based on a macroscopic inverse dynamic analysis of the center-of-mass of motion. Velocity-time data are fitted using an exponential function, after which instantaneous velocity is derived to compute the net horizontal antero-posterior ground reaction force (F), and the power output in the horizontal direction (P). Individual linear force-velocity relationships are then extrapolated to calculate theoretical maximal force (F0) and velocity (v0) capabilities, and underlying maximum horizontal external power output (Pmax). In this method, F and v are

averaged and plotted throughout the course of a sprint for each stance phase. The steps from maximal F through to those producing maximal v are subsequently used to plot the linear F-v relationship (Samozino et al., 2016). The entire F-v relationship is described by the maximal theoretical horizontal force that the lower limbs could produce over one contact at a null velocity (F0 expressed in N•kg^{-1}) and the theoretical maximum velocity that could be produced during a contact phase in the absence of mechanical constraints (v0 expressed in m•s^{-1}). A higher v0 value represents a greater ability to develop horizontal force at high velocities. (see Figure 18.2).

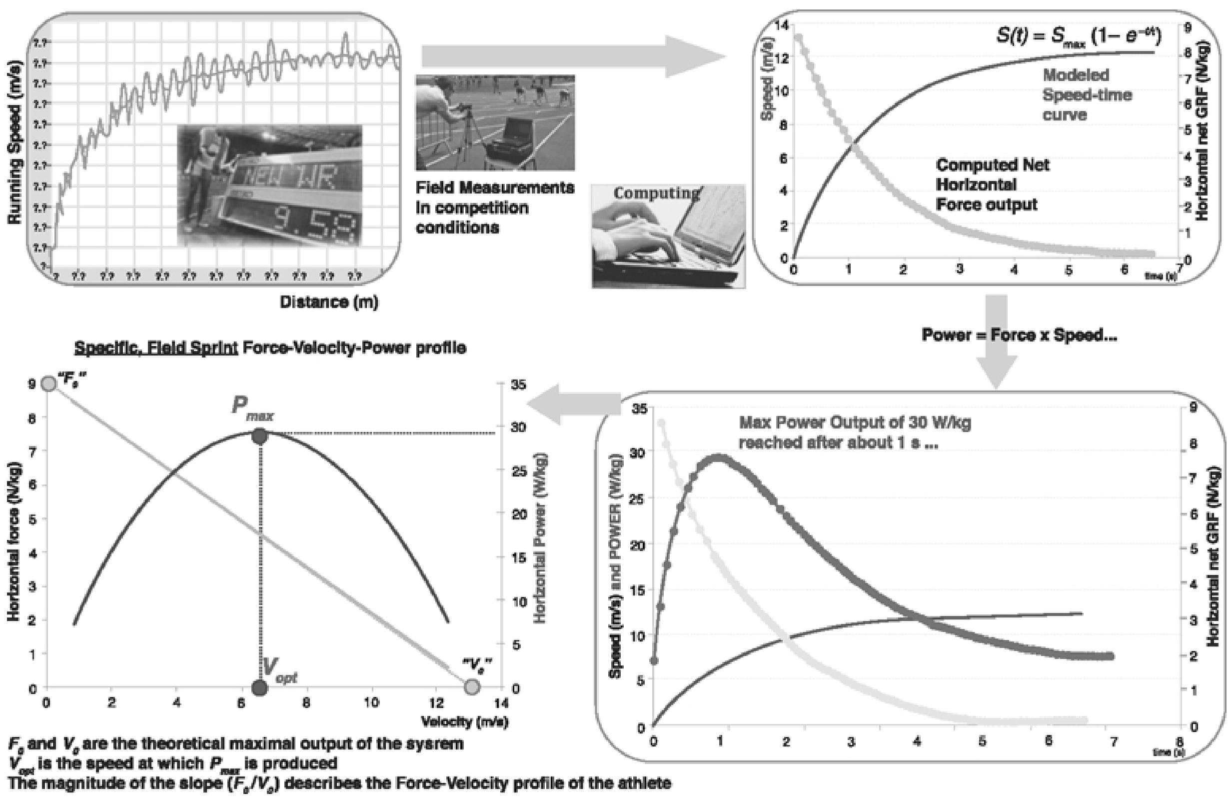

FIGURE 18.2 Force-velocity-power profile of Usain Bolt's world record.

Together with F0, v0, and Pmax, the entire mechanical F-v profile also includes the mechanical effectiveness of ground force application, which is described with two main variables explained above: RF (i.e., the ratio of the effective horizontal component of the GRF to the resultant GRF) and how quickly this ratio drops as the running velocity increases (decrease in the ratio of force, DRF). Therefore, determining the F-v profile is very useful in practice since an athlete can be identified in a force and velocity context,

which determines his/her weaknesses, and training can then be aligned accordingly on an individualized basis (Morin & Samozino, 2016). With this in mind, it is worth highlighting the usefulness and strength of this approach for estimating over-ground running sprint kinetics via a simple yet reliable field method with almost identical values to direct measurement via a sophisticated force-plate setup (Rabita et al., 2015; Samozino et al., 2016). This method has been shown to be sensitive enough to differentiate mechanical parameters between athletes with similar capabilities or playing roles and provide practical information to aid return to play from injury in rugby and soccer players (Cross et al., 2015; Mendiguchia et al., 2014, 2016). Furthermore, given the simplicity of obtaining the data required for this method, such as velocity-time measurements with an adequate sampling rate, for training and assessment purposes this profiling method would be easily used by strength and conditioning coaches and practitioners with timing gates, a radar gun, or even a recently validated iPhone app (MySprint) (Romero-Franco et al., 2016).

INDIVIDUALIZED TRAINING BASED ON F-V PROFILING

Strength and conditioning coaches and practitioners are very interested in the best training methods for improving sprinting performance. Several training methods have been widely used, including sprinting (Rumpf et al., 2016), technical skills (Bushnell & Hunter, 2007; Lockie, Murphy, Schultz, Knight, & Janse de Jonge, 2012), maximal power (Delecluse et al., 1995; McBride, Triplett-McBride, Davie, & Newton, 2002), reactive strength (plyometric training) (Sáez de Villarreal, Requena, & Cronin, 2012), ballistic training (Cormie, McGuigan, & Newton, 2010; Sheppard et al., 2011), and combinations of these methods (Harris, Stone, O’Bryant, Proulx, & Johnson, 2000; Ronnestad, Kvamme, Sunde, & Raastad, 2008), although inconsistent results have been achieved with many of them.

Strength and conditioning research has influenced the importance of traditional strength training in improving sprint performance via the transfer phenomenon. Thus, the question arises: “is classical ‘vertical’ strength work really effective in transferring and increasing the level of horizontal force output in trained athletes?” Horizontal force generation is a key factor in many sports, and therefore specific training to improve it is essential. The issue for training is that traditional strength-based resistance training may

not be the most specific way to develop the ability to apply force with a horizontal orientation since the majority of resistance training methods focus on working the lower limb muscles in a vertical direction. Although during sprinting both the horizontal and vertical components of GRF are necessary to the overall motion of the runner, the horizontal component has the most influence during acceleration (Brughelli et al., 2011; Morin et al., 2011; Morin, Slawinski, et al., 2015; Morin et al., 2012; Rabita et al., 2015). Recently, the existence of a possible transfer of lower-body strength training to sprint performance has been discussed, with a review of literature supporting the idea that sprint performance can be improved through strength gains (Seitz et al., 2014). However, this improvement is not systematic since many parameters affect the magnitude of improvement. Little is known about the effectiveness of a specific training program using exercises to improve the force-velocity-power associated with the horizontal component of GRF on sprint performance. It is likely that a greater transfer of resistance training can be achieved if the conditioning program emphasizes a similar motor pattern and contraction type (i.e., comparable mechanical properties) to the performance movement (Young, 2006). The importance of strength exercises for improving muscles having a determinant action during horizontal force application in acceleration must be noted (Contreras et al., 2016).

In addition, since adaptations are specific to the velocity used in training, it is worth considering this specificity over the entire F-v spectrum, which must be covered for training purposes. In consequence, the concept of “what force at what speed” emerges as a relevant factor for improving both acceleration and maximum speed. For F0 improvement it is important to produce high forces at low speeds, while for v0 improvement the application of force at high speed is most significant. Thus, the fundamentals of how to specifically and effectively train according to the F-v profile features are based on this velocity specificity principle, taking into account the different components of the F-v profile (F0, RF, Pmax, DRF, and v0).

The features explained above concerning F-v profiling could provide both useful information for sport practitioners and a simple, accessible, yet accurate method for more individualized monitoring and training of physical and technical capabilities. This method can be easily implemented

on a regular basis and can therefore be used for long-term monitoring and training processes (Morin & Samozino, 2016).

PRACTICAL APPLICATIONS: INDIVIDUAL PROFILING AND TRAINING PROGRAM

F-v profiling and associated components could provide very useful and practical information, allowing the selection of the most appropriate exercises for improving sprint performance and enabling the design of better training programs for different modalities by considering which component (F0, RF, Pmax, DRF, and v0) should be emphasized.

Since the F-v profile can be easily measured during sprint running, coaches could obtain valuable comparative information and guidance for individualized training or rehabilitation prescriptions.

In practical terms, if a training program is designed to improve sprint acceleration performance, the focus should be placed on increasing Pmax by improving its components (F0 and v0). This could be done by first comparing the relative strengths and weaknesses in each player's profile to the rest of the team (e.g., median or mean value) or published data for similar athletes, and then programming the training content depending on the distance over which sprint acceleration should be optimized.

The question for coaches is how to specifically target the different components of the F-v profile, and, although training for Pmax could be relevant depending on the orientation of the F-v profile towards force or velocity, the targeted programs for individuals could differ depending on whether a force-oriented or velocity-oriented profile dominates.

For practical purposes, it is interesting to divide exercises based on the targeting of different parts of the entire F-v spectrum as follows:

- Force side of the F-v: the focus of these exercises is the application of high forces at low speeds, leading to an improvement in the F0 and RF components of the F-v profile.
- Power side of the F-v: the focus of these exercises is the application of medium forces at medium speeds, resulting in an improvement in the Pmax component of the F-v profile.
- Velocity side of the F-v: the focus of these exercises is the application of low forces at high speeds, resulting in an improvement in the DRF

and v0 components of the F-v profile.

The features of each of the three components discussed above, and appropriate exercises for each, follow:

- F0 and RF category:

At the beginning of an accelerated run, a high horizontal force application is developed at a low velocity of motion. This early acceleration phase is characterized by a very pronounced inclination of the trunk and overall body, which helps in applying force in a horizontal direction. Thus, the main feature of this “high-force, low-velocity” phase is that the athlete applies much higher horizontal forces than when running faster. It is thus logical to assume that an exercise or training modality that could gather these features into a specific running pattern would be appropriate since it would target the development of the force side of the F-v spectrum.

A training modality that could best satisfy these considerations is the “Very Heavy Sled” (VHS) since it is an effective way of providing a good incline while applying high horizontal force at low speed, allowing the athlete to create and maintain conditions of high force, high forward lean, and high muscular activity in the main propulsion muscles such as the hip extensors.

Interestingly, very recently, a study using amateur soccer players showed the effectiveness of training with VHS (80% of body mass) over an eight week period, which led to marked improvements in the mechanical effectiveness of force application (F0 and RF) and in Pmax (Morin et al., 2016).

Thus, it seems that VHS is both a cost- and time-effective way of overloading the athlete, training both lower limb strength (i.e., general capacity) and the technical ability to apply this force effectively onto the ground (i.e., horizontally-oriented force).

- Pmax category:

After the first steps (about two seconds of initial application of force), maximal power is reached, which is the combination of optimal force and velocity at medium force (F0/2) and medium velocity (V0/2). These “optimal loading” conditions for improving sprint running performance

have been discussed (Petrakos, Morin, & Egan, 2016), particularly with regard to resisted sprints, although the criteria for determining optimal load for sprinting were based on non-significant alterations to technical components (i.e., kinematics of the unloaded sprint movement via a 10% decrement with respect to maximal velocity), rather than considering force or velocity components from the F-v profile as a reference. It is important to note that when Petrakos et al.'s criteria are applied, the features and conditions needed to develop horizontal force at a specific velocity at this stage of an accelerated run are limited, since with only a 10% velocity decrement the body cannot remain in a forward-inclined position for long and the athlete is forced to adopt a more vertical position quite quickly.

In line with this, very recently, researchers (Cross, Brughelli, Samozino, Brown, & Morin, 2017) analysed the "optimal load" on an individualized basis (i.e., the load which, for each individual, induces maximal power output), and the results appear to be highly individualized, with resistances of between 69–96% of body mass, corresponding to a velocity decrement of ~50% from maximal velocity (Cross et al., 2017). Technical and mechanical F-v characteristics were also found to be highly individualized (Cross et al., 2017).

Thus, it seems that using individualized sled resistances that lead to individual optimal load and optimal running velocity, i.e., the velocity at which maximal power is produced (close to V0/2 as shown by Cross et al., 2017) can provide an effective stimulus for maximizing horizontal power production, thereby improving the physical and technical capacities underlying sprinting performance (Morin et al., 2011; Morin, Slawinski, et al., 2015). It is also likely that increasing an athlete's Pmax will be associated with a better sprint acceleration performance, especially over short distances (e.g., soccer) and in collision sports (e.g., rugby) (Cross et al., 2017).

- DRF and v0 category:

As velocity increases over the acceleration phase, the conditions for force application change. For early acceleration, a high force at low velocity is required, but the athlete then needs to keep producing and applying a net horizontal force despite increasing movement velocity. At high running velocities, the body is essentially in a standing position (vertical), and the

knee is extended at touch-down and during the stance phase; in this situation, from a functional anatomy standpoint, the only action leading to a backward push of the foot on the ground is violent hip extension. This condition is a limiting factor in the continued application of force in a horizontal direction, and it has been shown that better sprinters tend to produce a higher RF and thus a higher mechanical effectiveness (i.e., a more horizontally-oriented GRF) at high velocity (Morin et al., 2012).

It is therefore reasonable to assume that an exercise modality that emphasizes the application of force at high velocity could be appropriate since it specifically targets the development of the velocity side of the F-v spectrum.

Given the importance of improvement in velocity (i.e., the velocity end of the F-v spectrum), several training modalities have been commonly used, including free sprinting, assisted and resisted sprinting, traditional strength-training, and plyometrics (Rumpf et al., 2016). The effectiveness of these training modalities is unclear (Rumpf et al., 2016), and it could be interesting for coaches to use more specific training based on the F-v profile, targeting the velocity side of the F-v spectrum with potential benefit for the v0 and DRF components of the F-v profile.

Sprinting may be the most specific type of training available to improve sprinting speed (Rumpf et al., 2016), probably due to an increase in velocity-specific force production with the same pattern of movement. However, improvements achieved via free sprinting are higher in untrained subjects than in trained athletes (Rumpf et al., 2016), and this issue should be considered in order to implement the F-v profile approach for optimized improvement in sprint velocity.

In light of the above information, and based on some preliminary results, the exercises most likely to be appropriate should allow the athlete to apply horizontal force in a high-velocity context. Taking into account that when athletes run at high velocities the body is in a standing position (vertical), with high activity in the hip extensors, it would be useful to reproduce specific and similar patterns during the application of force. The first exercise could be sled with light loads (about 10% of body mass) since this trains the ability to produce horizontal force at high running velocities and is thus an effective stimulus. Another possible exercise involves explosive backward propulsion on a scooter (testing in progress). Together with these exercises, other options that make sense mechanically (but are still to be

tested under controlled conditions) include over-speed training and the inclusion of a resistance during an assisted condition. Finally, but no less importantly, free sprinting would also be an effective stimulus for improving velocity capability, since most of the distance in a 50–80m sprint is run at velocities close to maximal velocity.

These types of exercises could therefore be an effective way to improve the DRF and v0 components of the F-v profile via the improvement of horizontal force production at high velocities.

CONCLUSION

Summarizing the practical details, when an athlete accelerates, the main mechanical need is to (1) produce force and (2) to transmit it effectively to the ground. These two actions must be repeated and performed at high speed. Thus, the main focus of training should be on the core and ankle stabilizer muscles as "transmitting" muscles, and the hip extensors as the main force generators. The latter may be trained using the very specific exercises "hip thrusts" and back extensions to strengthen these key muscles for forward acceleration. This chapter has focused on the mechanical factors underpinning sprinting performance based on the F-v approach; understanding these fundamentals of sprinting performance may allow coaches and practitioners to develop specific training programs to reinforce the main muscles affecting performance in acceleration running.

The main value of this approach is that the diagnostic and subsequent targeted training interventions are individualized, and frequent monitoring of program-induced changes in Pmax and its mechanical determinants can make this program more efficient and dynamic in terms of adaptation to individual changes over time.

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CHAPTER 19

Applied coaching science

Nick Winkelman

INTRODUCTION

In 1993, Jana Novotna was serving against Steffi Graf in the Wimbledon final, just one point away from winning the championship. Despite leading four sets to one, Novotna went on to conceded four straight sets, inevitably losing 6–4 to Graf in what can only be described as one of the most public displays of “choking” ever seen in modern sport. However, Novotna is not alone, as there are many other examples of clear winners losing their nerve in the final moments of a competition. Take, for example, Greg Norman, who was six strokes ahead of Nick Faldo going into the final round of the 1996 Masters and went on to lose by four strokes by the end of Sunday. From a team sport standpoint, fans will not forget the 2004 World Series where the New York Yankees, up three games to one against the Boston Red Sox, lost four straight games and the Commissioner’s Trophy.

While it is debatable whether the outcomes described above are examples of “choking” or comebacks, one fact remains, there was a pivotal moment where the winning side started underperforming and/or the losing side started outperforming the competition. Whichever the case, there was a shift in motor skill behavior and decision making that enhanced the fortune of one competitor at the expense of the other. While some might chalk this up to a bad day, poor luck, or a lack of resolve, others may question these surface level explanations in search of underpinning reasons. What’s more,

while the opening examples of “choking” provide extreme instances of failure in competition, there is the more common experience of athletes not delivering the same level of performance in competition as they commonly do during practice. It is this latter observation that sets the stage for this chapter, and in doing so requires a fundamental question to be asked. How can coaches increase the probability that the performance their athletes achieve in practice is the one they deliver during competition?

To begin answering this question, it is important to define the difference between practice performance and competitive performance. Specifically, Soderstrom and Bjork (2015) define practice *performance* as “the temporary fluctuations in [motor skill] behavior or knowledge that can be observed and measured during or immediately after the [practice] process,” while competitive performance or what will now be referred to as *learning*, “refers to the relatively permanent changes in [motor skill] behavior or knowledge that support long-term retention and transfer to [competition].” Thus, as illustrated by the examples of “choking” in sport, coaches are advised against viewing practice performance as a proxy for learning. Rather, learning can only be assessed in the absence of the stimulus that caused it (i.e., practice), which positions competition as the single most important measure of motor skill retention and transfer. In her seminal book *Choke*, Sian Beilock provides further support for this line of reasoning, defining “choking as suboptimal performance, not just poor performance,” and noting that “it is performance that is inferior to what you can do and have done in the past” (Beilock, 2010). Thus, while “choking” is often associated with performance anxiety and labeled as failed mental fortitude, an equally viable explanation would be the re-contextualization of “choking” as a failure of the learning process.

To illustrate the impact of practice performance on learning, it is valuable to review the two pathways by which learning can take place. Take, for example, a child learning to ride a bike. At first their parents would have given them training wheels, allowing them to get a sense of balancing on the bike and learning how to pedal with enough speed where the training wheels become unneeded. Once the parents feel the child is ready, they take the training wheels off, and after a few falls, the child has figured out how to ride the bike safely. From a motor learning standpoint, this scenario is an example of emergent or implicit learning. That is, the parents were not explicitly telling the child how to steer, pedal, maintain

posture, and visually navigate the sidewalk; rather, they likely gave them basic instructions (e.g., “pedal faster”) that were of no consequence to the actual movement process required to ride the bike. Thus, this movement pattern emerged out of the child’s determination not to fall and their desire to ride their bike like the rest of the neighbor kids. As noted, this is an example of an *implicit learning* pathway, which can be defined as learning that occurs through practice that emphasizes experience and limits explicit information, leading to a physical understanding of rhythm, sequence, and execution that can be measured through performance, but not through factual recall (Kleynen et al., 2014). In other words, while easily able to ride their bike, the child would not have much in the way of words to describe how they achieved this childhood feat.

In contrast to the example above, consider the same child’s experience during Karate class. It is likely that the child would have an instructor, suggesting that instruction would be used to facilitate the learning process. For example, the choku-zuki or “straight punch” would be a fundamental movement that the child would learn as they transition from their white belt to their yellow belt. In learning this movement, the instructor would teach the child proper body position, describe how their clenched fist should remain palm up and just above their belt, and further describe how the punch should be thrown in concert with the recoiling of the opposing arm. In this instance, the motor learning strategy would be considered deliberate or explicit. Specifically, the instructor would assume that the child would focus on the movement instructions while performing the straight punch, allowing them to learn the skill faster than had they been left to their own devices. What’s more, the instructor would also assume that, in time, the child’s ability to throw the straight punch would become more automatic, requiring less explicit attention from the child. This would be particularly important if the child was to demonstrate movement sequences or use the straight punch in a competitive setting. Thus, distinct from the implicit learning, the *explicit learning* pathway can be defined as learning that generates verbal knowledge of movement performance (e.g., facts and rules), involves cognitive stages (i.e., awareness) within the learning process, and is dependent on working memory involvement (Kleynen et al., 2014).

Considering the examples provided above, it is necessary to highlight that, while distinct, both implicit and explicit learning pathways are

essential to the motor learning process (Vidoni & Boyd, 2007). However, from a coaching standpoint, it is important to recognize the pedagogical or coaching strategies associated with each learning pathway, along with the mediating factors that guide the differential use of each strategy. With this in mind, it is valuable to first examine the underpinning neuroscience associated with the learning process. Specifically, a coach's awareness of the neural correlates (i.e., brain regions) connected to implicit and explicit learning, and the general influence of attention and memory on this process, will assist them in selecting coaching strategies that are both task type and experience level appropriate.

NEUROSCIENCE OF IMPLICIT AND EXPLICIT LEARNING

Before discussing how best to apply implicit and explicit learning strategies, it is important to review the mediating role of attention and memory within the learning process and the associated neuroscience. In his seminal work, *The Principles of Psychology*, William (1890) captures the essence of attention when he states that "My experience is what I agree to attend to. Only those items which I notice shape my mind—without selective interest, experience is utter chaos." These words highlight the importance of attention within the human experience, as people are only aware, and thus a product of that on which they focus. The alternative would find people, upon waking, having gained skills (e.g., playing the piano) for which they have no recollection of ever practicing. While this osmosis-esque version of super-learning may become a reality in future, for now one can be confident in knowing that learning is a product of what one pays attention to (Gallagher, 2009). Extending this line of thinking, Kahneman (2011) notes that people "dispose of a limited budget of attention that you can allocate to activities, and if you try to go beyond your budget, you will fail" (Miller, 1994). Thus, while the capacity to focus one's attention exists, this capacity is limited and requires people to selectively attend to the information that is deemed most relevant for a given context. From this perspective, the role of the coach is to deploy strategies that help the athlete direct their *attentional spotlight* in a way that best serves the learning process.

To understand how attention influences learning, it is important to first appreciate how what an athlete attends to impacts where the information is stored in the brain. Thus, just as there are explicit and implicit learning strategies, there are also explicit and implicit memory systems. Specifically, explicit memory, also known as declarative memory, are conscious memories of facts and rules pertaining to a motor skill, while implicit memory, also known as procedural memory, are the sub-conscious memories associated with the control and performance of a motor skill (Vidoni & Boyd, 2007). Put simply, explicit memory is required to describe a movement, while implicit memory is required to perform it. To highlight the impact coaching can have on the way memories are formed during the learning process, consider the following example of two baseball players being asked the same question by a reporter: "What are the key strategies to effective batting performance?" *Athlete one* might respond by providing rules and facts about batting, noting the best mental cues to use during practice, while *athlete two*, to the reporter's disappointment, may respond by stating that they have no idea and pointing out that they just get up and swing. While fictional, these responses are not too dissimilar to notable quotes from famed golfer, Jack Nicklaus and Irish Rugby International, Ronan O'Gara, where Nicklaus stated that "concentration is a fine antidote to anxiety" and O'Gara proclaimed that "[he] knows how to kick a ball, but [has] no idea how to teach someone to kick a ball." These examples highlight how information (i.e., explicit and implicit) about the same motor skill can be stored in distinct memory systems, and that the ability to perform a movement is not dependent on one's ability to verbally describe it (e.g., Lam, Maxwell, & Masters, 2009). Thus, as will be shown later on, the way information is learned and stored has a lot to do with the robustness of the motor skill, especially when exposed to the stress of competition.

To illustrate how memory formation influences the learning process, it is important to now examine the distinct brain regions associated with the explicit and implicit memory systems. Specifically, there are three key areas that are involved in generating and integrating explicit memories as they relate to motor skill learning. These areas include, but are not limited to, the medial temporal lobe (hippocampus and associated cortices), the prefrontal cortex (the "seat of conscious processing"), and the dorsolateral prefrontal cortex (DLPFC) (Vidoni & Boyd, 2007). To appreciate how these brain regions are used in explicit memory formation and integration, consider the

preceding baseball example once again. Specifically, re-visiting the answer of *athlete one* to the question of how to hit a baseball, it is evident that their coach would have used, at least in part, explicit learning strategies to teach them how to hit. That is, from a neuroscience standpoint, *athlete one's* hippocampus and associated cortices would have been responsible for processing any instructions or feedback provided by their coach, ensuring that this information was readily available during batting practice or to answer a reporter's question about hitting performance. What's more, in applying the coach's instructions while practicing, *athlete one* would have depended on their DLPFC to integrate any explicit thoughts held in working (short-term) memory with the visuospatial information (i.e., motion of pitcher and ball speed) required to hit the ball (Jueptner et al., 1997; Vidoni & Boyd, 2007). Thus, the DLPFC plays an important role in integrating the information contained within the explicit memory system and the motor actions that information is meant to influence within the implicit memory system.

The implicit memory system involves a greater number of brain regions, which is not surprising considering its role in motor control. These brain regions include, but are not limited to, the cerebellum, the basal ganglia, and the cortical motor areas: the premotor cortex (PMC), the supplementary motor area (SMA), and the primary motor cortex (M1). Again, it is helpful to examine the function of these brain regions in the context of the baseball example. Specifically, while it is evident that *athlete one* has more explicit memories (i.e., facts and rules) of how to hit than *athlete two*, likely due to how they were coached, both athletes require the formation of implicit memories associated with the requisite motor control needed to hit a baseball. Thus, in learning how to hit, both athletes would have depended on their cerebellum to tune and optimize the hitting pattern. That is, the cerebellum is responsible for integrating sensory input and motor output in a way that allows the motor system to make real-time adjustments to the movement (Ivry, 1996; Vidoni & Boyd, 2007). This fine tuning of the movement is a hallmark of implicit learning.

In addition to the cerebellum, the athletes would have depended on their basal ganglia to integrate explicit information with the implicit motor action and switch between motor tasks (i.e., hit the baseball, drop the bat, and run to first base). It is not surprising then that the basal ganglia operates like a "switchboard", connecting disparate brain regions that are critical for motor

control, notably the “motor circuit” regions (i.e., putamen, thalamus, SMA, and PMC) and the DLPFC described in the explicit memory section (Vidoni & Boyd, 2007). Damage to this region of the brain has been shown to slow the learning process and disrupt the influence of explicit information on performance and learning (Boyd & Winstein, 2006).

Finally, the athletes would have depended on their primary motor cortex (M1) to initiate the swing in addition to fine tuning the coordination of the hitting motion. This fine tuning can be attributed to the role M1 plays in determining direction of motion and force output during movement (Vidoni & Boyd, 2007). Thus, like the cerebellum, the M1 is central to real-time motor control and the development of the implicit motor plan (Lohse, Wadden, Boyd, & Hodges, 2014). Working alongside the M1 are the PMC and the SMA. The PMC, via the basal ganglia, is responsible for integrating explicit information relating to the sequence of a motor action (Vidoni & Boyd, 2007). Thus, if the coach was to give instructions around how to move the bat in space (i.e., swing path), the PMC would play a central role in integrating this information with the implicit motor plan for swinging a baseball bat. In contrast, the athletes would have depended more on their SMA when they were practicing without explicit information (i.e., coach input) (Vidoni & Boyd, 2007). That is, the SMA would leverage task-intrinsic feedback that could be used to modify the swing path, for example, on subsequent repetitions. However, this process would function in the absence of explicitly derived instruction or feedback. Interestingly, the PMC is highly active during early stages of learning where explicitly derived information is needed (Grafton, Hazeltine, & Ivry, 1995); however, as learning progresses there is a reduction in activity in the PMC in favor of increased activation of the SMA, highlighting its role in coordinating implicit motor actions (Toni, Krams, Turner, & Passingham, 1998).

In summary, it is important to place the functional role of the disparate memory systems (i.e., explicit and implicit) and their associated brain regions within a practical context. That is, while the two systems interact, highlighting the importance of explicit and implicit learning strategies, it is important to understand that becoming overly reliant on explicit information can be detrimental to learning, especially during the rigors of competition (Baumeister, 1984; Masters, 1992). Specifically, research has shown that a form of neural competition can exist between explicit memory systems and implicit memory systems (Poldrack et al., 2001). Thus, while

the explicit memory system is important during early stages of learning, independent of whether the information is explicitly derived from the coach or autogenously from the athlete, it can become detrimental to the execution of the implicit motor plan once learning consolidation has occurred (Song, 2009). That is to say, if the athlete starts thinking about a pattern for which there is already an implicit basis for automaticity, the thinking will disrupt the athlete's ability to naturally self-organize the pattern in relation to task and environmental demands (i.e., "choking"). In support of this line of reasoning, Song (2009) notes the following when discussing the interaction between the explicit and implicit memory systems:

> Motor learning may initially rely on more explicit and prefrontal areas, but after extended practice and expertise, shift to more dorsal areas, but thinking about the movement can shift activity back to the less skilled explicit areas. Although many explanations may be derived, one could argue that these athletes show that even when years of practice has given the implicit system an exquisitely fine-tuned memory for a movement, the explicit system can interfere at the time of performance and erase all evidence of implicit memory.

Therefore, it is important that coaches understand how to place explicit and implicit coaching strategies within the context of where the athlete is within their learning process. What's more, it is important to understand how to deploy explicit coaching strategies in a way that supports the long-term learning and retention of desired motor skills, but doing so in a manner that will not thwart the expression of those skills in a competitive arena (i.e., choking and/or over-reliance on coaching feedback). To start seeding this information into a practical framework, the next section will discuss the integrative role of explicit and implicit coaching strategies within stage models of motor skill learning (e.g., Anderson, 1982; Fitts, 1964).

STAGE MODELS OF MOTOR SKILL LEARNING

Stage models of motor skill learning (e.g., Anderson, 1982; Fitts, 1964) suggest that individuals will transition from a cognitive or declarative stage (i.e., explicit memory)—whereby explicit rules are acquired concerning

goal-relevant aspects of the motor skill, to an autonomous or procedural stage (i.e., implicit memory)—whereby goal-relevant aspects of the motor skill have been consolidated (Song, 2009) and are no longer consciously attended to during motor skill execution (Masters, 1992). Thus, independent of the coaching strategies used, the athlete learning a novel skill will naturally leverage their explicit memory system during the initial stages of the learning process and depend more on their implicit memory system during later stages of the learning process. That is to say, the athlete would naturally "pay attention" or be aware of performing the movement at first, however, once they lay down an implicit understanding of the movement process (e.g., coordinating upper and lower body in an effort to dribble a basketball) they would naturally be able to divert their attention to more relevant features of the environment (e.g., the approaching opponent or the teammate best suited to receive the ball and shoot a jump shot). To illustrate this point, it is instructive to examine the work of Beilock, Carr, MacMahon, and Starkes (2002) and Castaneda and Gray (2007), who showed that experts perform better when they focus on features of the environment (i.e., implicit learning), while novices benefit from focusing on the motor skill itself (i.e., explicit learning). In-line with these findings, Beilock et al. (2002) recommends that during early stages of learning it would be "beneficial to direct performers' attention to step-by-step components of the skill, [while] at later stages of performance, this type of attentional control may be detrimental."

While the conclusion of Beilock et al. (2002) suggests that explicit learning strategies should be used with novices and implicit learning strategies with experts, coaches would be ill-advised to apply such a literal translation to their practice. For example, Masters (1992) identified an interaction between the way a motor skill is learned (i.e., practice) and one's susceptibility to "choking" during a high-stress testing condition (i.e., competition). Specifically, one group of novices were asked to practice a golf putt while focusing on a specific set of instructions (i.e., explicit learning group), while a different group of novices practiced the same putt with no instructions and a secondary-task designed to deter explicit focus on the movement (i.e., implicit learning group). As one might expect, the novices in the explicit learning group "sunk" more putts during the practice sessions than the implicit learning group, although both groups significantly improved over the four practice sessions. However, this trend inversed

when the participants were asked to putt under a high-stress test condition where they were led to believe that they would receive a monetary reward based on the evaluation of their performance by a golf professional. This illustrates two key points. First, as noted in the introduction, successful performance in practice is not necessarily indicative of an equally successful performance under stressful conditions. Second, implicit learning provides a certain level of protection over performance loss or “choking” during competition. Thus, this latter point suggests that there could be some benefit to using implicit learning strategies with a novice, especially as it relates to success in competition.

Similarly, just as Masters (1992) has provided evidence for the benefit of implicit learning strategies for novices, Wulf and Su (2007) and Bell and Hardy (2009) have provided evidence that explicit learning strategies are beneficial for experts. Specifically, both studies showed that focusing on the outcome of a golf shot (e.g., club motion, club face position, or flight path of ball) resulted in significantly better performance and learning than focusing on the movement process (e.g., arm action or wrist position) in both novices and experts. Thus, this line of inquiry suggests that it is not information, in a general sense, that disrupts implicit motor learning, rather, it is the direction of focus (i.e., external or environment vs. internal or body) encouraged by the instruction that determines whether there is a positive or negative impact on learning. What’s more, similar research on the use of analogies has shown that instructions that highlight the movement outcome or the effect the movement should have on the environment (e.g., Sprinting: Sprint as fast as you can past the 10-meter cone or push away from the start line as fast as you can) through an analogous cue (e.g., Sprinting: Drive out and away from the start line like a jet taking off), serve to support implicit learning as opposed to thwart it (Lam et al., 2009). Put simply, coaches can think of the explicit memory system as a conductor in an orchestra, guiding the general direction or outcome of the composition, while the implicit memory system is the many musicians that must coordinate their playing, just as joints and muscles must coordinate motion, generating a piece of music far more complex and beautiful than anything that would be created in isolation. Therefore, just as a conductor cannot and should not attempt to play every instrument, coaches should avoid explicit instructions that require the athlete to focus on one aspect of the movement at the expense of the whole, independent of whether they are a novice or an expert.

In summary, it is important for coaches to recognize the necessary interplay between explicit and implicit learning strategies, as it is impossible to stop an athlete from thinking just as it is impossible to stop a coach from coaching. Thus, it is not a matter of picking sides, rather, coaches need to know when and how to apply explicit and implicit learning strategies to steward the athlete’s journey from novice to expert. For this reason, the next two sections will provide explicit and implicit coaching frameworks for optimizing performance and learning.

EXPLICIT COACHING FRAMEWORK

The *explicit coaching framework* is chiefly concerned with the impact thinking has on the motor skill learning process. That is, while athletes may autogenously derive explicit thoughts concerning the movement they are learning, especially if the new skill is similar to a movement they know, this section is primarily concerned with the thoughts that are encouraged by the instruction and feedback provided by the coach. Specifically, instruction is used to focus an athlete’s attention on the most important characteristics of the motor skill being learned prior to movement execution, while feedback is used to inform the athlete of the outcomes (i.e., knowledge of results) and performance (i.e., knowledge of performance) associated with an already executed movement. Thus, instruction and feedback can be used to shape the *attentional spotlight* and focus the athlete on the most relevant features of the motor skill being learned. With this in mind, the following section will provide strategies for optimizing instruction and feedback in the context of the factors that mediate their influence on the learning process (e.g., experience level).

Instruction

Instruction can be considered any verbal information that is provided to the athlete prior to them performing a given motor skill. The purpose of instruction is to facilitate the athlete focusing their attention on the most relevant feature of the motor skill being learned. For example, if a coach was teaching an athlete how to perform a vertical jump and they noticed that the athlete was not fully extending through their hips during the ascent

of the jump, then they may select an instruction or cue that, if focused on during the jump, will help the athlete improve this attribute of the motor skill. This example illustrates an important assumption that needs to be confirmed for any coach interested in optimizing the effectiveness of their instructional strategies. Specifically, instructional strategies are only as effective as they are relevant to the primary motor skill errors. That is to say, if a coach directs their instruction or cue at an irrelevant feature of the movement (e.g., cueing the upper body during a sprint when the source of the error exists within the lower body), then the end result will not be favorable, even if the substance of the instruction is representative of the strategies to follow (Polsgrove, Parry, & Brown, 2016). Thus, the first step to providing the athlete with explicit information that will support the learning process, is to ensure that the substance of the information is relevant to overcoming the identified movement error. Both Carson and Collins (2011) and Winkelman (2017) have provided models that suggest the importance of identifying the source of the motor skill error as a precursor to the deployment of explicit and implicit learning strategies.

While the conceptualization of how to instruct has been broadly researched, the psychological domain of *attentional focus* has provided the greatest level of breadth and depth concerning the optimization of instruction and cueing (for a review, see Wulf, 2013). Specifically, an athlete can focus internally on the motion of their body (i.e., movement process) or externally on the effect their movements have on the environment (i.e., movement outcome) (Wulf et al., 1998). More specifically, instruction encouraging an internal focus will commonly direct attention towards joint motion (e.g., “extend your hips” or “flex your knees”) or muscle function (e.g., “squeeze your glute” or “lengthen your hamstring”), while an external focus encourages the athlete to focus their attention on the movement outcome (e.g., “jump as high as you can” or “sprint towards the finish line as fast as you can”) or the effect on the environment (e.g., “explode off the ground during the jump” or “push the ground back during the sprint”). To illustrate the application of these instructional strategies, consider the following example of a coach teaching an athlete how to perform the Olympic lifts. In one instance, the coach could provide an internal cue by telling their athlete to “focus on explosively extending through your hips,” alternatively, the coach could provide an external cue by telling their athlete to “focus on explosively

pushing the ground away." While the instructions carry the same message (i.e., get off the ground "explosively"), the internal cue calls attention to the body (i.e., hips) and the external cue calls attention to the environment (i.e., ground). These examples lead to an intuitive question, under what conditions is it best to use instructions or cues that encourage an internal focus versus an external focus? To answer this question, it is helpful to briefly review the research that has contrasted the differential influence of internal and external focus on practice performance and learning.

While attentional focus has been widely studied, the following paragraphs will primarily focus on the literature pertinent to athletic performance (e.g., jumping and sprinting). For instance, Wulf, Zachry, Granados, and Dufek (2007) examined the effects of attentional focus on vertical jump performance. The results showed that novices jump significantly higher when they adopt an external focus (i.e., "focus on the highest rung of the Vertec") compared to an internal focus (i.e., "focus on getting the tips of your fingers as high as possible"). Wulf and colleagues (Wulf & Dufek, 2009; Wulf, Dufek, Lozano, & Pettigrew, 2010) confirmed these findings and found that underpinning improved vertical jump performance were higher lower body impulses and joint moments and lower EMG in the lower body within the external focus condition, which suggests that a more efficient movement pattern is achieved (Lohse, Sherwood, & Healy, 2010; Vance, Wulf, Tollner, McNevin, & Mercer, 2004). What's more, these findings have been extended to horizontal jumping, with all known research on the differential effects of internal and external focus showing that adopting an external focus of attention leads to significantly further jump distances during practice (e.g., Porter, Anton, & Wu, 2012; Porter, Ostrowski, Nolan, & Wu, 2010; Wu, Porter, & Brown, 2012).

Similar to the jumping literature, the current evidence suggests that athletes learning to sprint would be well advised to adopt an external focus of attention. Specifically, Ille, Selin, Do, and Thon (2013) and Porter, Wu, Crossley, and Knopp (2015) have provided evidence that novices exhibit superior sprint performance over 10m and 20m when they adopt an external focus opposed to an internal focus. However, both Porter and Sims (2013) and Winkelman, Clark, and Ryan (2017) have shown that as experience increases, so does the benefit of the athletes' normal focus, which is commonly referred to as the control condition within attentional focus

research. This finding makes sense, as one would expect that with experience comes the development of the implicit motor plan. This motor plan does not require as much explicit attention control, as the pattern has been consolidated and now exists within automatic motor control structures (Lohse et al., 2014). Thus, from a practical standpoint, it is beneficial to allow the experienced athlete to perform an increased number of repetitions without instructional reminders, as this will only strengthen their ability to autonomously deploy the motor skill when instruction and feedback is not available from a coach (e.g., competition).

Finally, it is worth noting that the vast majority of research supports the findings presented above, showing that novices unquestionably benefit from an external focus of attention (Wulf, 2013), and that the advantage of a normal focus becomes evident as experience level with the motor skill increases (e.g., Stoate & Wulf, 2011; Wulf, 2008). However, it is worth noting that research has consistently shown that highly experienced individuals still benefit from an external focus of attention (e.g., Bell & Hardy, 2009; Ille et al., 2013; Wulf & Su, 2007). What's more, in support of these findings, research has shown that an external focus of attention promotes greater movement velocity (e.g., Vance et al., 2004), force (e.g., Halperin, Williams, Martin, & Chapman, 2016), endurance (e.g., Marchant, Greig, Bullough, & Hitchen, 2011), and efficiency (e.g., Lohse & Sherwood, 2012). Considering these findings, it is not surprising that an external focus of attention has also been associated with greater cerebellar and primary motor cortex activation than an internal focus of attention (Zentgraf et al., 2009). Thus, one can argue that instruction encouraging an external focus, while explicit in nature, supports implicit learning to a greater degree than an internal focus. Moreover, this argument aligns with the *constrained action hypothesis*, which suggest that an internal focus "constrains the motor system by interfering with automatic motor control processes that would 'normally' regulate the movement"; while an external focus allows the "motor system to more naturally self-organize, unconstrained by the interference caused by conscious control attempts" (Wulf, McNevin, & Shea, 2001). For this reason, coaches should prioritize the use of externally focused instructions and cues, especially as it relates to optimizing the coordination required to perform in practice and express that performance in the context of competition (see Winkelman, 2017 for an applied model).

Feedback

While instruction provides guidance prior to the execution of a motor skill, feedback provides the necessary information required to help the athlete reflect and apply new information to subsequent practice trials. From a practical perspective, the feedback given after the completion of a practice trial is often interwoven with the resultant instruction or cues meant to influence the ensuing practice. Thus, feedback plays a primary role in guiding motor skill learning by providing the substance required to continuously refresh instructions and cues.

Two forms of feedback have been identified and will be the focus of this section. First, *knowledge of results* (KR) provides the athlete with information about a quantitative outcome. This could be how high they jumped, how fast they covered a distance, their accuracy and thus proximity to a fixed point, or successful attempts as represented by a percentage. Alternatively, coaches can provide their athletes with a *knowledge of performance* (KP), which directly relates to the movement process or technique that led to a given outcome. This type of feedback is often subjective and requires the expertise of a coach. Examples of KP can be further broken down into *prescriptive feedback*, whereby the coach provides the athlete with specific instruction around how to correct an observed movement error (e.g., “on your next repetition, focus on getting off the ground faster”), and *descriptive feedback*, which simply requires the coach to describe the error without providing any corrective instruction (e.g., “your lower body was excessively flexed when you hit the ground”). Collectively, KR and KP are both important to guide the learning process, however, the application of these feedback strategies need to be considered in terms of the type of skill and the experience level of the athlete.

For coaches to understand how best to apply feedback strategies, it is important to recognize the fundamental purpose of feedback. Specifically, the central role of feedback is to provide the athlete with pertinent information that they would not otherwise be aware of if not provided externally. Thus, coaches should seek to provide KR and KP that is not redundant to the task-intrinsic information associated with a given motor skill. To help illustrate this point, it is instructive to review the recommendations for providing feedback discussed by Magill (1994).

> 1. If the skill being learned does not allow the learner to detect critical sensory feedback information, such as when a limb's spatial position cannot be seen, then augmented feedback is required.

Recommendation one suggests that augmented feedback is required when visual or proprioceptive feedback is not available to the athlete or not associated with an established implicit motor plan. Thus, for an athlete just learning how to Olympic lift or to sprint, for example, it may be important to provide the athlete with KP on bar position in the case of the former and body position in the case of the latter. However, as the athlete develops an implicit motor plan and the associated sensory-motor representation (i.e., feel for the movement), then this information may become redundant to the task-intrinsic feedback now available to them.

> 2. If the skill being learned involves acquiring a new concept that is essential for successful performance, such as understanding a unit of measurement, then again, augmented feedback is required.

Recommendation two encourages coaches to use feedback, specifically KR, when this information can help the athlete benchmark their performance against a quantitative outcome. For example, providing an athlete information about jump height or jump distance can help them to benchmark their current performance against the sensory consequences of achieving that outcome. They can then compare the *good* reps to the *bad* ones, which helps the athlete use sensory feedback associated with the execution of the motor skill to further refine their performance during practice.

> 3. If the skill provides the learner with all the essential feedback information needed to learn the skill, then augmented feedback may not be needed.

As noted earlier, feedback is only impactful when it decreases uncertainty and provides the athlete with new information. Thus, coaches should be critical to provide feedback that is not available to the athlete and prioritized based on the most critical movement errors that, if corrected, would allow learning to continue.

4. Skills for which the outcome is easy to determine but the limb coordination requirements to produce high-level performance are difficult to develop require knowledge of performance about limb movement characteristics.

This final recommendation is highly specific to accuracy based tasks. These tasks could include passing a rugby ball, hitting a golf or tennis ball, kicking a field goal, or shooting a basketball. In all cases, there is task-intrinsic feedback about the outcome, however, less information would be readily available around the coordination required to achieve the desired outcome, especially for those that are novices. Thus, building on the last point, the context of the skill is often a key determinate of which type of feedback is most appropriate.

While the preceding recommendations will guide the selection of appropriate feedback, there is still a need to understand how often feedback should be provided, commonly referred to as feedback schedules. The basis for this latter line of inquiry dates back to Salmoni, Schmidt, and Walter (1984), who suggested that there is a *guidance effect* associated with too much feedback. That is, feedback "acts as guidance, with immediate reward providing more guidance and perhaps leading to a reliance on such feedback for performance, and hence poorer performance in a transfer test" or during competition (Salmoni et al., 1984). Put simply, if feedback is provided too often, athletes may become dependent on feedback, possibly ignoring intrinsic sensory feedback that is important for establishing internal error-detection mechanisms, and they may also be encouraged to make too many explicit corrections during practice, which could make it difficult to establish a stable motor pattern (Anderson, Magill, Sekiya, & Ryan, 2005).

From a practical standpoint, feedback should only be given as often as is needed to provide the athlete with the information necessary to progress their performance and learning. This will typically mean that more feedback is provided when an athlete is initially learning a skill, with a progressive reduction in feedback as the athlete gains experience. However, each time the difficulty of the skill is increased (e.g., progressing from a hang clean to a power clean), there will be a period of time where feedback is also increased. Thus, there is an interaction between experience level, skill complexity, and the amount of feedback required to support the learning

process (Guadagnoli, Dornier, & Tandy, 1996). In an effort to help coaches optimize their feedback frequency, strategies have emerged to help overcome the negative impact of too much feedback. These strategies include *bandwidth feedback* (e.g., Lee & Carnahan, 1990), where feedback is only provided if the error is outside of a preset parameter or bandwidth (e.g., KR is only provided if bar speed during a bench press drops below a certain velocity or KP is provided only if a certain technical error is observed); *faded feedback* (e.g., Winstein & Schmidt, 1990), where feedback is systematically reduced over a given number of practice trials (e.g., 100% feedback for first set of 10 trials, 66% feedback for second set of 10 trials, and 33% feedback for third set of 10 trials); *summary feedback* (e.g., Schmidt, Lange, & Young, 1990), where feedback is provided as a summary following a certain number of trials (e.g., KR about jump height is provided after five jumps have been performed or KP about prominent technical errors is provided after three sprint repetitions have been performed); *average feedback* (e.g., Young & Schmidt, 1992), where feedback is represented as an average following a certain number of trails (e.g., KR concerning sprint times is averaged and provided to the athlete after three sprint efforts or KP about the most common error observed across three repetitions of an agility drill); and *self-controlled feedback* (e.g., Chiviacowsky & Wulf, 2005; Janelle, Kim, & Singer, 1995), where the athlete is given the option to request feedback whenever they feel it is necessary (e.g., based on the task type and difficulty, athletes can request KR and KP at the rate that they feel is most appropriate for them). Note that all of these feedback scheduling strategies have evidence to support their efficacy, however, as noted earlier, this is often mediated by the type of skill, the complexity of the skill, and the experience level of the individual (Guadagnoli et al., 1996). Thus, coaches are encouraged to pay close attention to the progress within practice and the level of retention in competition, using these observable factors as guides to support the selection of an optimal feedback strategy.

In summary, instruction provides a basis for guiding the motor learning process, while feedback plays a central role in refining the motor learning process. This interaction creates a learning loop, ensuring that explicit coaching strategies steward the learning process, but not at the expense of a robust implicit motor plan. In-line with this conclusion is the evidence showing that an external focus helps protect against choking under pressure

(e.g., Lawrence, Gottwald, Khan, & Kramer, 2012; Ong, Bowcock, & Hodges, 2010). Thus, in light of the strategies discussed above, coaches are advised to keep their messages brief as to not overload working memory (i.e., one major point per repetition), provide feedback at a frequency that guides the learning process without creating dependence on the coach, and to ensure the substance of the message encourages an external focus of attention when at all possible.

IMPLICIT COACHING FRAMEWORK

The *implicit coaching framework* is primarily concerned with the ecological dynamics associated with the learning process. Specifically, ecological dynamics describes how behavior emerges in accordance with the interaction of an organism, in this case the athlete, and their environment (Gibson, 1979). Within motor learning theory, an ecological or dynamical systems view is often associated with a constraint-led approach to teaching (Newell, 1985; Newell, 1986). That is, motor behavior is said to emerge as a result of the constraints inherent to the body, the environment, and the task. Thus, a change to the body (e.g., strength or mobility), the environment (e.g., the surface), and/or the task parameters (e.g., rules of a game) will result in a different movement solution (Newell, 1986). From this perspective, a constraint-led approach would suggest that in certain instances, a coach could manipulate constraints to encourage one movement solution over another. Intuitively, coaches do this all the time, however, it may be a function of chance rather than choice. Therefore, the following section will focus on how to effectively use a constraint-led approach to support learning through an implicitly emphasized pathway.

Constraint-led approach

From a coaching perspective, it is best to consider the constraint-led approach as a conceptual framework that can be used to design learning rich environments. Specifically, coaches can systematically select constraints within the context of practice and specific drills to encourage the formation of adaptable “coordinative structures” (i.e., technique) (Anson, Elliott, & Davids, 2005). Thus, “constraints define the boundaries within

which [the] human neuromuscular system must operate and, therefore, shape the emergence of patterns of coordination and control" (Glazier & Davids, 2009). This idea that movement emerges in accordance with internal and external constraints was referred to by Bernstein (1967) as the "degrees-of-freedom problem" (e.g., Vereijken, Emmerik, Whiting, & Newell, 1992) and is now commonly described as the "Bernstein problem" (Turvey, 1990). The notion that movements are a solution to a problem provides coaches with an accessible metaphor for designing practice. That is, coaches can view themselves as teachers, the athlete as their student, and movement as the subject being taught. Therefore, practice is designed to pose a series of problems (i.e., drills or tactical scenarios) that the athlete must answer by searching for the most effective movement solution.

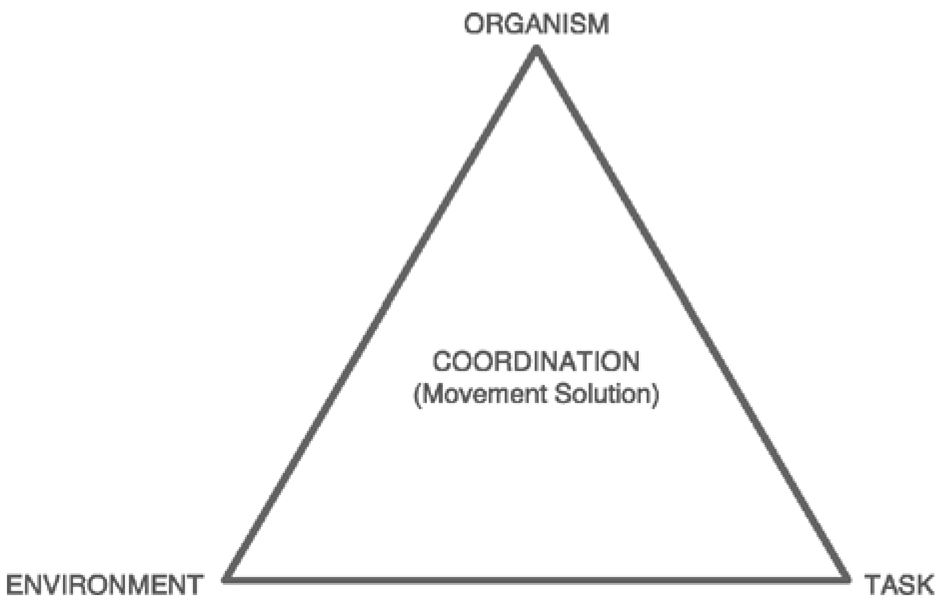

FIGURE 19.1 Newell (1986) interacting constraints model.

To illustrate this last point, consider the following examples. First, imagine a coach trying teaching their athlete how to squat for the first time. Suppose that they notice the athlete's knees consistently going inward (i.e., valgus) despite providing explicit instruction to focus on vertical alignment. In this instance, if instruction is ineffective, then the coach can use a constraint to help the athlete self-correct. Specifically, a common constraint used in this scenario would be to place an elastic mini-band around the knees (i.e., *task constraint*) and instruct the athlete to "keep tension through the band" as they squat. This constraint provides new sensory information

about the knee position, increasing the “signal” and, thus, the salience of the error to be corrected. Second, if the same coach is instructing a different athlete how to perform a kettlebell swing and finds that they are not fully extending their hips during the completion of the motion, then they may decide to use a *spatial constraint*. Specifically, the coach can have the athlete swing the kettlebell in front of a wall. This limits the athlete’s ability to leave the kettlebell too far forward, encouraging effective hip extension as to avoid hitting the wall. Thus, while a change in proprioceptive sense led to the change in the last example, in the present example, it would be the presence of new visual information that drives the change in movement behavior. Finally, consider a coach who has identified that their athlete tends to look down when attempting to cut or side-step an opponent while on offense. In this case, the coach can deploy *spatial* and *temporal task* constraints to encourage the athlete to perceive and act quicker than they currently are. Specifically, the coach can design a 5m × 5m box, marked by cones in each corner, and have the athlete in question stand in one corner and face a defender in the diagonal corner. The coach would then instruct the athlete, ball in hand, to sprint forward and attempt to exit the upper left or right sides of the box without being tagged by the defender. The box provides the spatial constraint, limiting the amount of movement options, while the defender provides the time constraint, limiting how much time the athlete has to make their decision. This environment creates a safe and repeatable opportunity for the player to work through the error and improve their ability to pick-up the correct visual information, allowing them to anticipate the defender’s movement and side-step in a game-relevant context. The key similarity in the examples noted above, which qualifies why these strategies are referred to as implicit, is that the athlete would not be aware of the specific reason for the improvement, however, they would be quite aware that they are making progress. Thus, unlike explicit learning strategies, constraint-led implicit strategies allow learning to take place outside the athlete’s conscious awareness of the source of improvement.

To place these examples in a broader context, it is helpful to understand the various categories of constraints. Newell (1986) presented the first theoretical model proposing how movement emerges from the interaction of constraints that exist within the organism, environment, and task (see Fig. 19.1). From an organism standpoint, there are two major categories of constraints, structural and functional (Glazier & Davids, 2009; Newell,

1986). Structural constraints are relatively stable over time and include genetic (e.g., muscle fiber type) and anthropometric (e.g., height, weight, and limb length) features (Shemmell, Tresilian, Riek, & Carson, 2004). However, structural constraints can change, albeit slowly, with improvements in strength, power, and flexibility being exemplars. Conversely, functional constraints are more susceptible to rapid change and include psychological attributes such attention, memory, intention, perception, emotion, and decision-making (Glazier & Davids, 2009; Kelso, 1997). Thus, as highlighted by the *explicit coaching framework,* the instruction, cues, and feedback we use operate as informational constraints that directly influence the behavior and movement solutions deployed by athletes.

As the name implies, environmental constraints include all constraints external to the organism. This would include light, temperature, surface, implements, and gravity (Glazier & Davids, 2009). As one might assume, these constraints are more difficult to manipulate, as most coaches cannot quickly change temperature, altitude, and/or the type of surface that they are playing on. What's more, it is for this reason that many movement behaviors become ubiquitous in sport, as they emerge as a direct consequence of a constant environment. While most environmental constraints are constant, those that can be varied are often associated with the task itself and can be defined as such.

Task constraints are a form of environmental constraint (Newell & Jordan, 2007) that directly relate to the desired outcomes of the movement (e.g., lifting the weight or making the shot). Specifically, task constraints include the space the movement is being performed in, the time the movement can be performed in, and the goals, rules, and equipment associated with the movement behavior. While the sport dictates space (i.e., field size), time (i.e., game time), and rules at one level, the opponent, in team sports, is equally able to further manipulate the space (e.g., pushing a player into touch in rugby) and time (e.g., charge a player, forcing them to quickly make a decision) an athlete has to achieve a given outcome via a specific movement behavior. Thus, constraint couplings become ubiquitous in sport and typically create the boundaries for teaching an athlete how to play a given sport; however, it is equally viable to manipulate these constraints within the context of practice to encourage one movement solution over another. Therefore, whether trying to improve the accuracy

with which an athlete kicks and passes, or how that same athlete coordinates the major upper and lower body lifts in the weight room, all movement is subject to modification through a constraint-led approach.

In summary, movement behavior is constantly being nudged by the constraints that exist within and outside of the human body. From birth, constraints guide and influence our development (Thelen, Fisher, & Ridley-Johnson, 1984), placing the environment front and center as the first coach/teacher one meets in life. What's more, there is a strong evolutionary basis for implicit learning (Reber, 1992) and, thus, the importance of constraints. This is not surprising considering that movement emerged long before one had the ability to think about movement (Sugarman, 2002). For this reason, coaches are encouraged to define the stable and variable constraints that exist across the organism, the environment, and the task, relative to their sporting context, as these constraints will impose the largest pressure on learning. In identifying these constraints, coaches can prioritize how best to manipulate their influence on the learning process. For example, an athlete who lacks the requisite relative strength and power (i.e., organismic constraints) to effectively accelerate may benefit from additional work within the weight room, as increased sprinting on the field will not improve these qualities to the same degree. Conversely, if a coach has identified a player who needs to improve their acceleration ability, however, their relative strength and power is already established, then it may be best to use environmental and task constraints to encourage improvements in the coordination associated with their acceleration. As illustrated by these examples, the constraint-led approach can serve to inform an athletic profile, providing coaches with a framework to map and prioritize where and how time should be spent to support the development of the athlete.

CONCLUSION

The primary objective of every coach is to guide the learning process, encouraging progressive improvements in practice performance that transfer to the competitive environment. As discussed, when a gap emerges between the performance observed in practice and competition, an athlete is often labeled as "choking." However, from a skill acquisition standpoint, this gap is also a reflection of the quality of the learning process. Thus,

coaches are encouraged to actively monitor and assess learning outside of the context with which learning is meant to take place (i.e., practice). From a sport coaching perspective, this is as simple as benchmarking an athlete's performance in practice versus competition. While a gap may have to do with susceptibility to anxiety and worry, this cannot explain all underperformance. Thus, coaches can use this as feedback to adapt their teaching and their approach to designing learning environments. Equally, a strength and conditioning coach can benchmark their effectiveness by having their experienced athletes perform a given lift without any initial instruction. This serves to see what information has been retained and can be applied without the explicit guidance of the coach, highlighting any implicit learning that has taken place. In a way, the quality of the learning observed within the athlete acts as a constraint on the way the coach deploys explicit and implicit learning strategies. For example, an athlete that has difficulty transferring performance in practice, when a coach is present, to the competitive environment, where the coach is absent, may depend too much on explicit guidance. Similarly, an athlete who is struggling to understand a drill or make progress within a given lift may benefit from explicit information that externally guides their attention towards the desired outcomes. Thus, while all motor learning must find a resting place within the implicit memory system, the pathway taken to get there will be highly individualized and guided by the seamless integration of explicit and implicit coaching strategies.

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